Metrology with Atomic Clocks

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Part I: Introduction and review:
Atomic clocks and applications

Part II: A modern atomic clock:
The mercury-ion optical clock

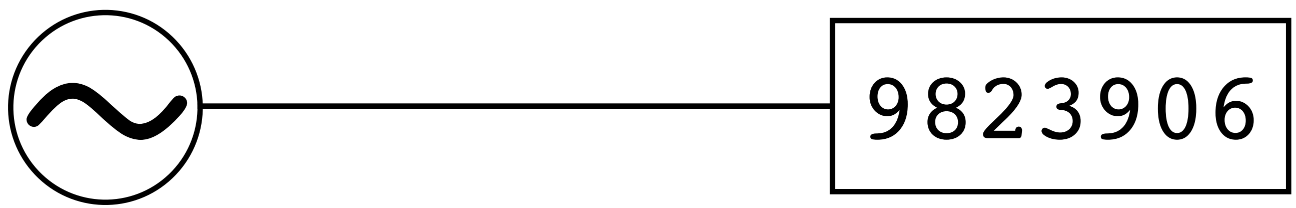
QUEST 2004

National Institute of Standards and Technology
Technology Administration, U.S. Department of Commerce

What is a clock?

An Oscillator
(Generates periodic events)

A Counter
(Counts and displays events)



Period Δt

Frequency $\nu = 1/\Delta t$

Count time
intervals

What is a clock?

An Oscillator
(Generates periodic events)

$$\Delta t = 1 \text{ day}$$

$$\nu \sim 10^{-5} \text{ Hz}$$

A Counter
(Counts and displays events)

August 2004

Sun	Mon	Tue	Wed	Thu	Fri	Sat
1	2	3	4	5	6	7
8	9	10	11	12	13	14
15	16	17	18	19	20	21
22	23	24	25	26	27	28
29	30	31	1	2	3	4

What is a clock?

An Oscillator (Generates periodic events)	A Counter (Counts and displays events)

Other canonical examples:

Mechanical pendulum	——	Gears and clock face
Quartz crystal	——	Electronic counter

Now: *What makes a clock a good time standard?*

What makes a time standard?

- For a standard, want clock with high stability and accuracy
  - *Stability*: ability to produce identical successive time intervals

$$\Delta t_i = \Delta t_j,\ \forall\ i, j \qquad \text{i.e.,} \qquad \frac{d\nu}{dt} \longrightarrow 0$$

  - *Accuracy*: ability to produce the same frequency as other clocks

$$\nu \longrightarrow \nu_0 \qquad \text{i.e.,} \qquad \Delta t_i \longrightarrow \frac{1}{\nu_0}$$

Accuracy requires an additional ingredient:
stable (unperturbed) reference

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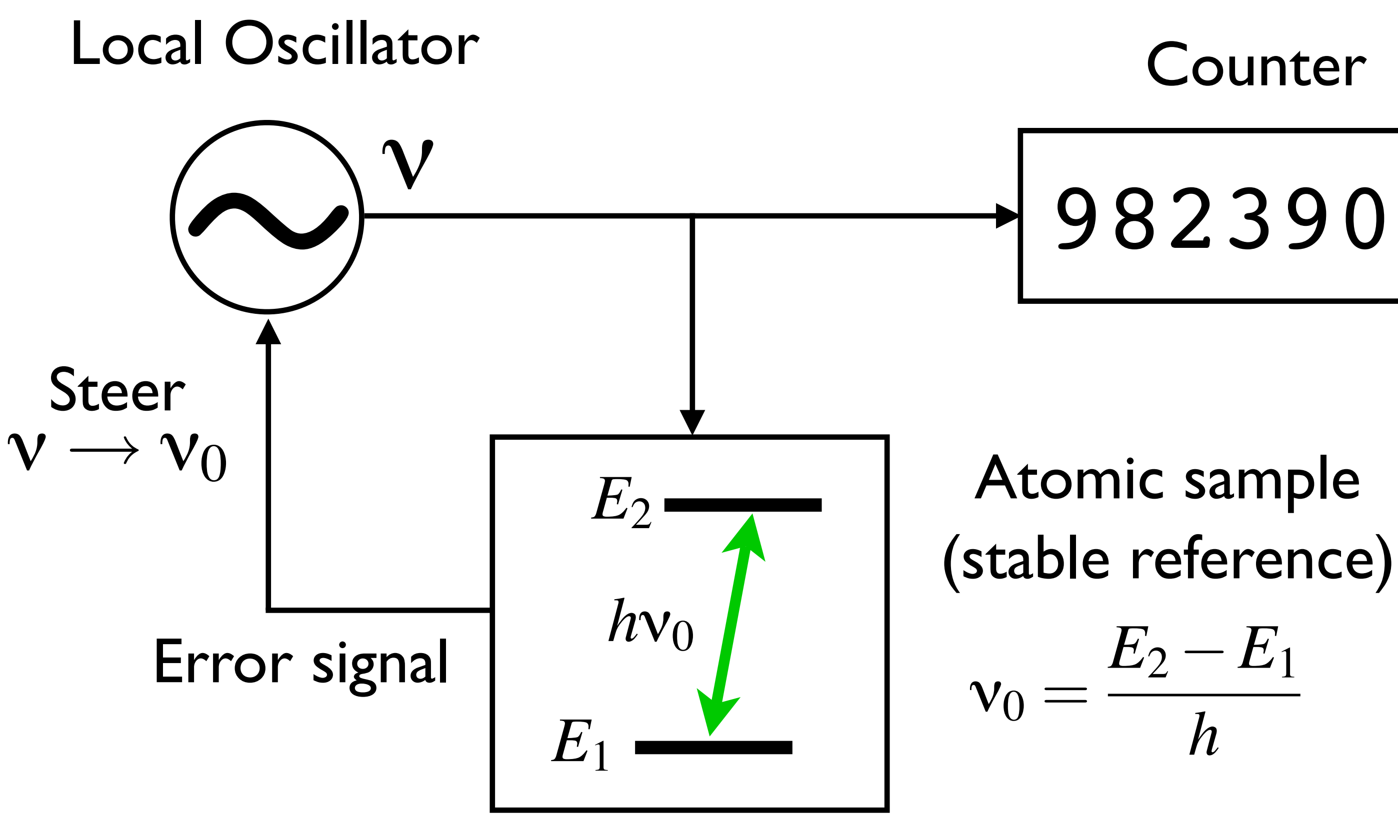
Basic idea of an atomic clock



Characterizing clock performance

- Stability characterized by Allan deviation $\sigma_y(\tau)$ for averaging time τ, with frequency fluctuations $\Delta\nu_{\mathrm{rms}}$.

$$\sigma_y(\tau) \approx \left\langle \frac{\Delta\nu_{\mathrm{rms}}}{\nu_0} \right\rangle_\tau$$

Quantum projection noise limit for an atomic clock:

$$\sigma_y(\tau) \approx \frac{1}{2\pi\nu_0\sqrt{N T_{\mathrm{R}} \tau}}$$

T_{R} : (Ramsey) Interrogation time

N : Number of atoms

- Limit to accuracy: uncertainty in correcting for changes in transition frequency relative to that of unperturbed atoms

Families of atomic clocks

Transition frequency →

Confinement ↓

	Microwave	Optical
Vapor Cell/ weak trap	H Maser Compact Cs, Rb Hg+ (large N)	
Beam/fountain/ cold atoms	Cesium, rubidium	Calcium
Tight confinement	Hg+ (small N)	Single ion clocks, Optical lattice clocks

Microwave frequency clocks

- Includes all "traditional" and commercial atomic clocks
- Based on ground-state hyperfine transitions:

Species	ν_0 (GHz)
H	1.420 405 751 770(3)
Rb	6.834 682 610 904 29(9)
Cs	9.192 631 770 (exact)
Hg^+	40.507 347 996 841 6(4)

- Several different technologies to probe these transitions

Microwave frequency clocks

Vapor Cell/ weak trap	H Maser Hg+ (large N) Compact Cs, Rb	Trade accuracy for high stability *or* compactness
Fountains	Cesium, rubidium	Can achieve good stability and accuracy
Tight confinement	Hg+ (small N)	Trade stability for accuracy (Obsolete)

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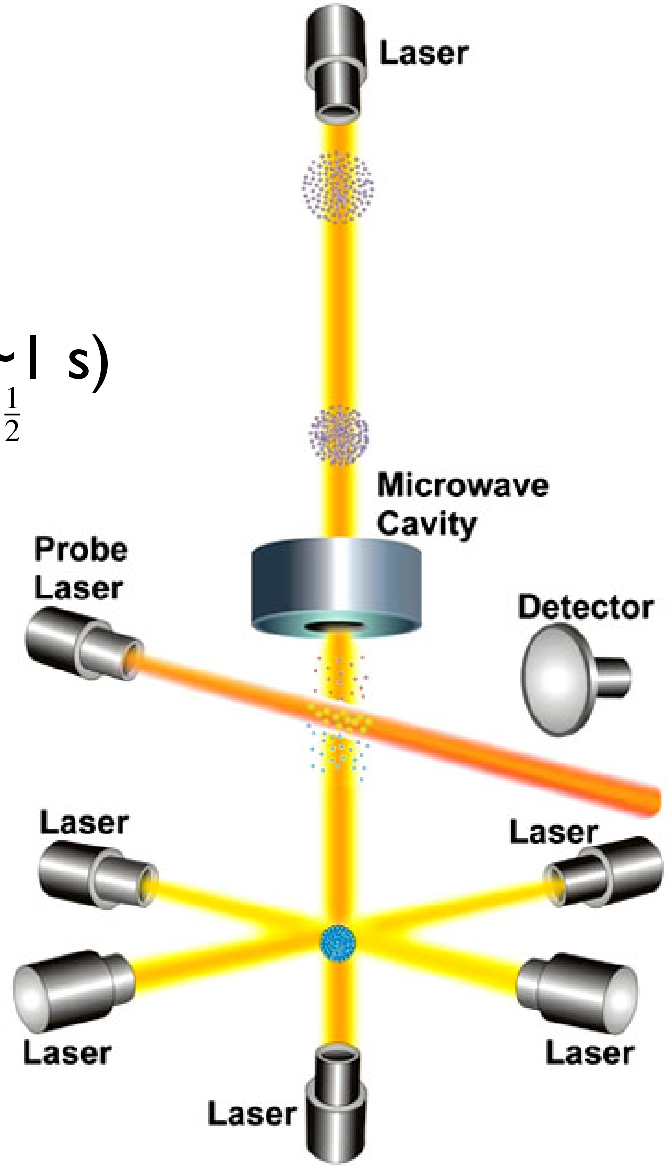
Cesium clocks

- Ground-state hyperfine transition defines SI second, all "absolute" frequency measurements are made vs. cesium.

- Fountain geometry maximizes probe time (~1 s) stability can approach $\sigma_y(\tau) \sim 2 \times 10^{-14}\tau^{-\frac{1}{2}}$

- Important systematics:
  - Doppler, 2nd order Doppler
  - Zeeman shifts
  - Blackbody radiation
  - Phase shifts in microwaves
  - Collisional shifts (lower for Rb)



Cesium clocks

•Cesium is *still* the most accurate clock
  Fractional frequency uncertainty $\sim 1 \times 10^{-15}$

1 s in 30 million years

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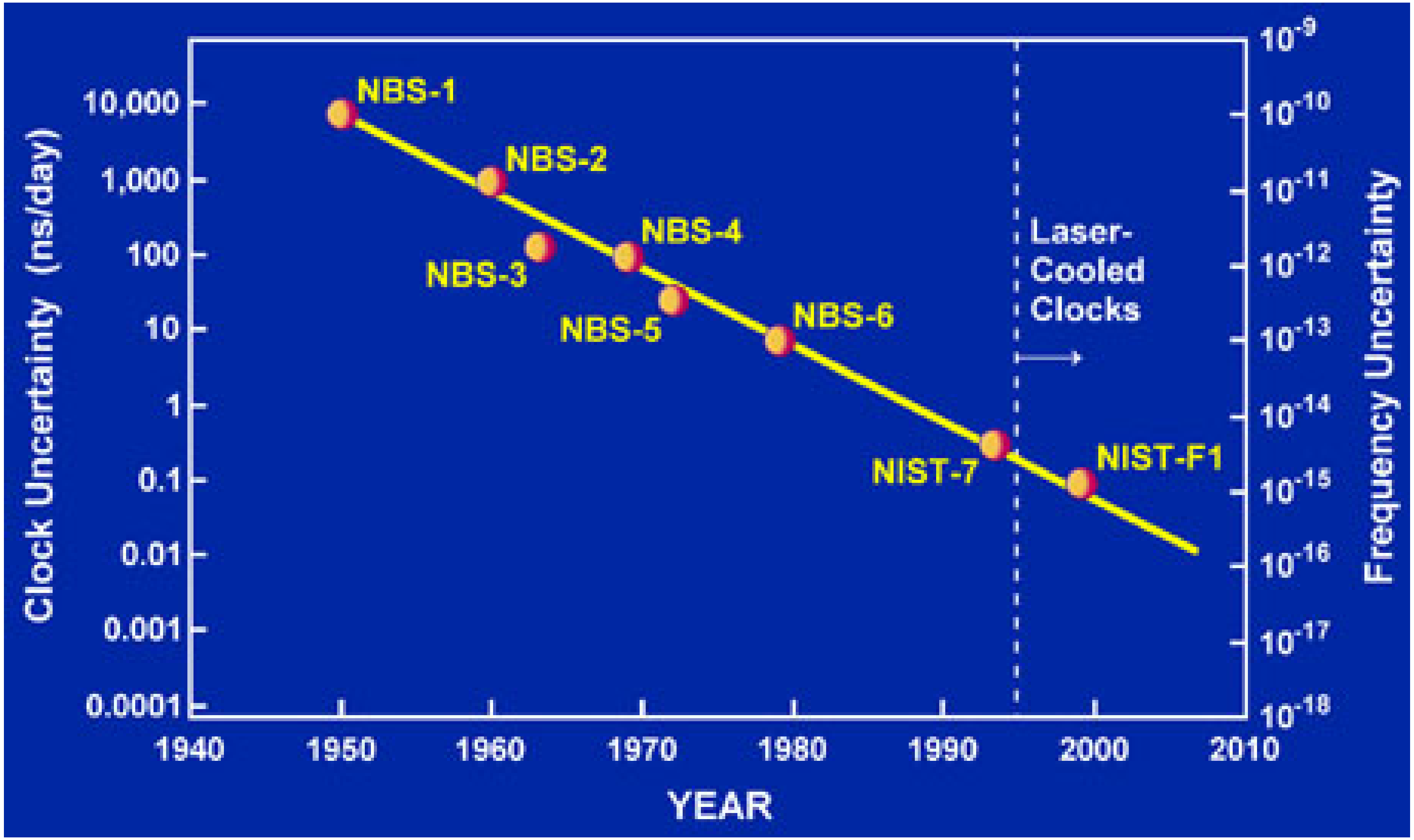
Cs clocks



Cesium clocks

•Cesium is *still* the most accurate clock
Fractional frequency uncertainty $\sim 1 \times 10^{-15}$

1 s in 30 million years...
or 1 ns in only 11 days.

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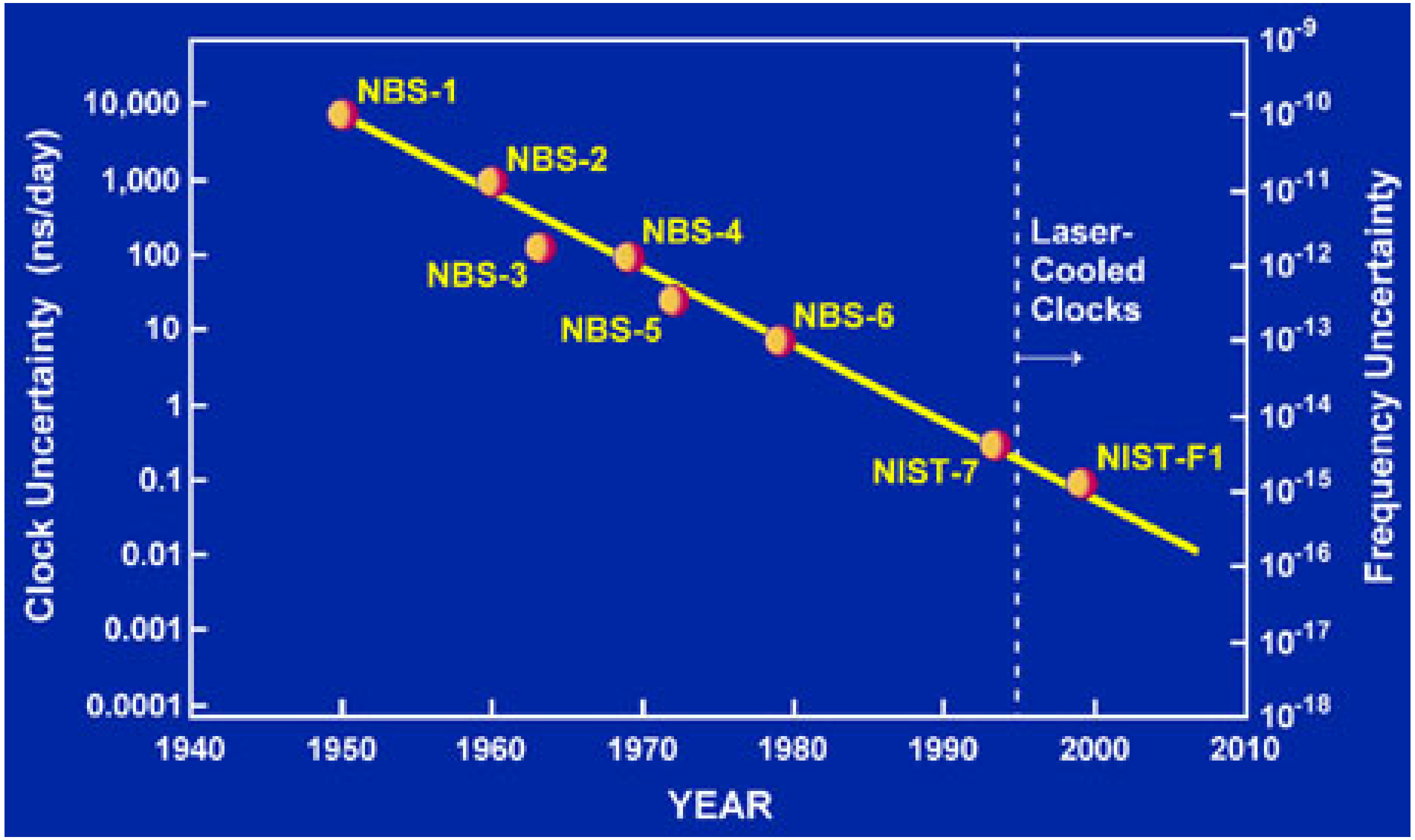
Cs clocks



Optical frequency clocks

- Higher transition frequency ⇒ higher stability
- Use optical transition instead of microwave

Recall stability limit: $\sigma_y(\tau) \approx \dfrac{1}{2\pi\nu_0\sqrt{NT_R\tau}}$

examples:

Cs fountain: $N = 10^6$ atoms, $\nu_0 = 9\ \mathrm{GHz},\ T_R = 1\ \mathrm{s}$

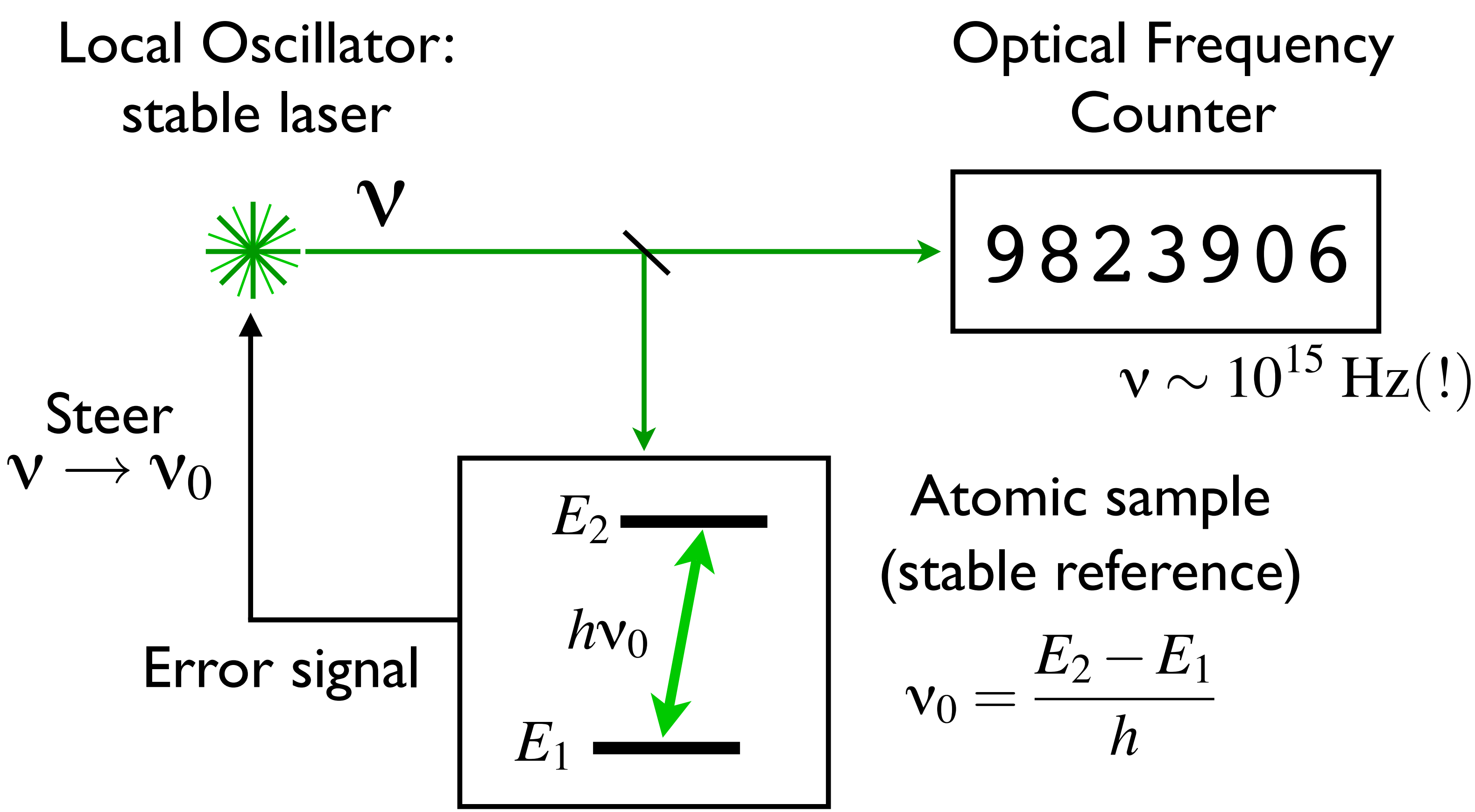
$$\Longrightarrow\ \sigma_y(\tau) \sim 2 \times 10^{-14}\tau^{-\frac{1}{2}}$$

Hg+ optical clock: $N = 1$ ion, $\nu_0 = 10^{15}\ \mathrm{Hz},\ T_R = 30\ \mathrm{ms}$

$$\Longrightarrow\ \sigma_y(\tau) \sim 1 \times 10^{-15}\tau^{-\frac{1}{2}}$$

- Increase in stability enables high accuracy for single ion.
- Extremely high stability for optical clock with large *N*.

Optical frequency clocks



- Local oscillator is stable laser (not quartz crystal)
- Need to count frequency of light
    - -Only recently practical

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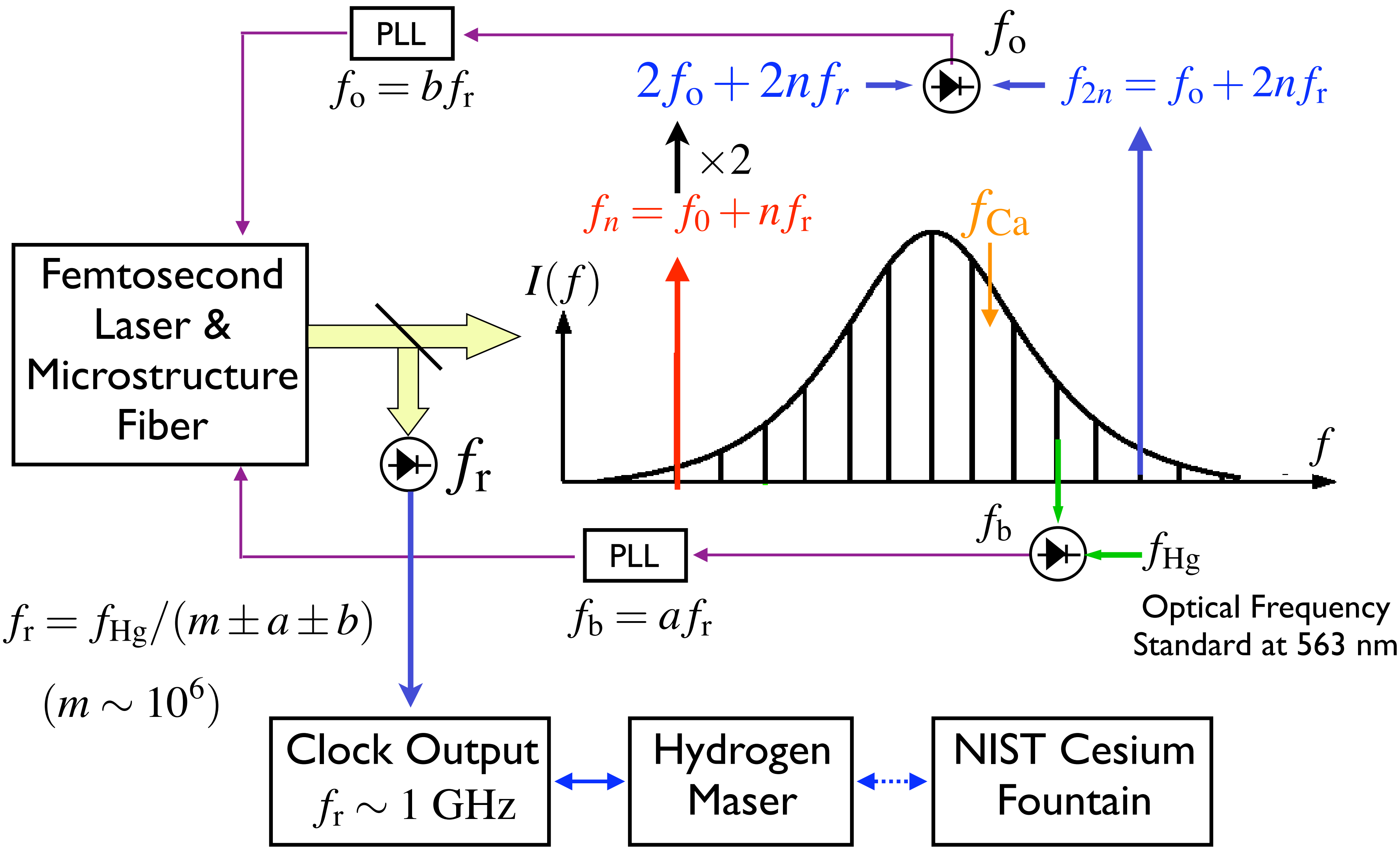
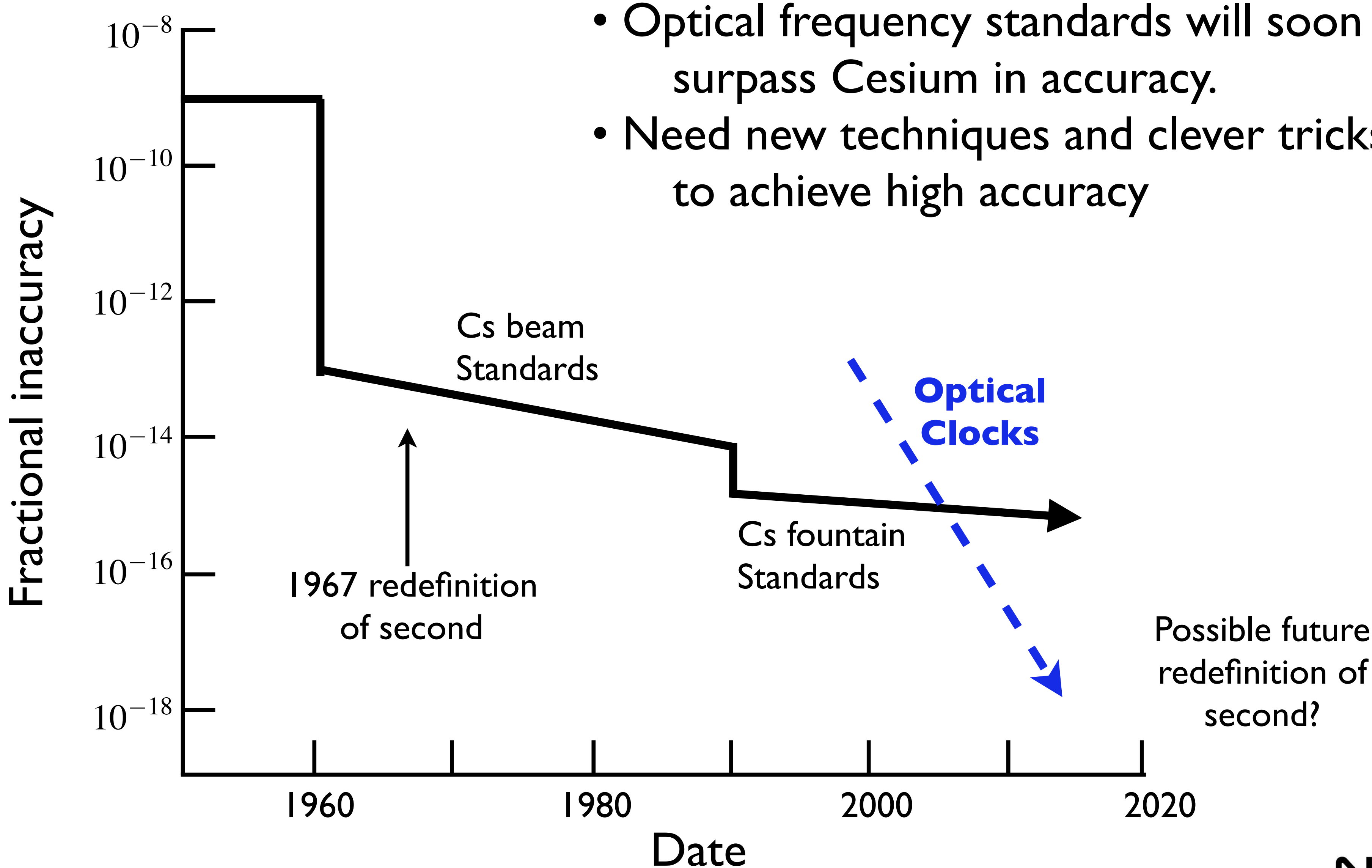
Femtosecond comb system



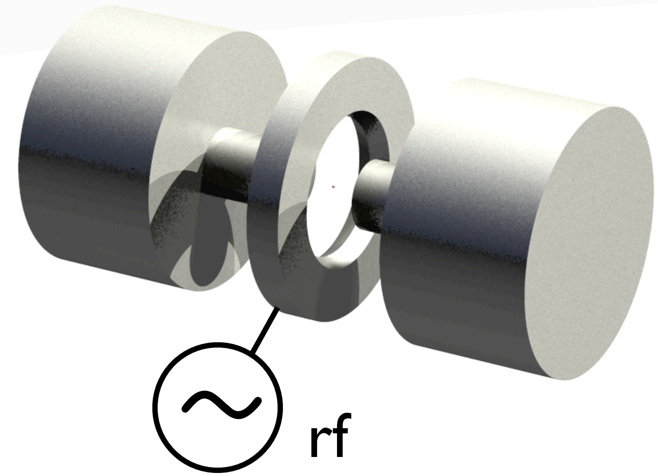
S.A. Diddams, *et al.* Science **293**, 825 (2001)

Optical frequency clocks

- Optical frequency standards will soon surpass Cesium in accuracy.
- Need new techniques and clever tricks to achieve high accuracy



Trapped ions in an rf trap



• No static **E** or **B** fields.

• Trap acts on total charge of ion,
not internal structure

•Trap ion at pseudopotential minimum (trap center)
⇒ Trapping fields at ion location approach zero

• Can operate in tight-confinement (Lamb-Dicke) regime
⇒ First-order doppler free.
2nd-order doppler shift expected to limit accuracy $\frac{\Delta\nu}{\nu_0} \sim 10^{-18}$

• Long storage times possible, ⇒ long probe times

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Trapping neutral atoms

- An optical clock with large *N* might be expected to demonstrate high stability, approaching $\sigma_y(1\ \mathrm{s}) \sim 10^{-18}$ but high accuracy is harder.

- Traps for neutral atoms work by perturbing internal structure
  - Magnetic traps bad for clocks
  - AC stark shifts in optical traps

⇒ Usually can only probe atoms in free-fall for a clock (Fountain, released from MOT, etc.)

But, atoms move during free-fall
- Maximum probe time is limited
- Motion through probe beam can cause frequency shifts

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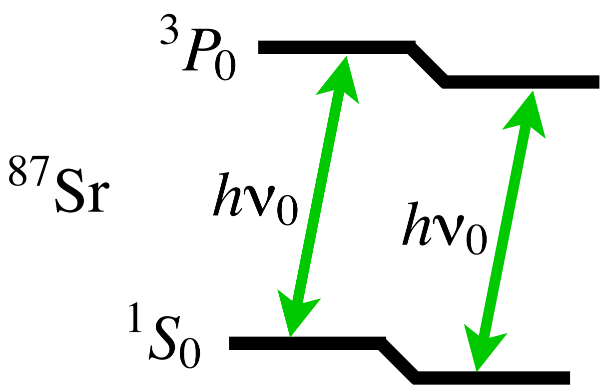
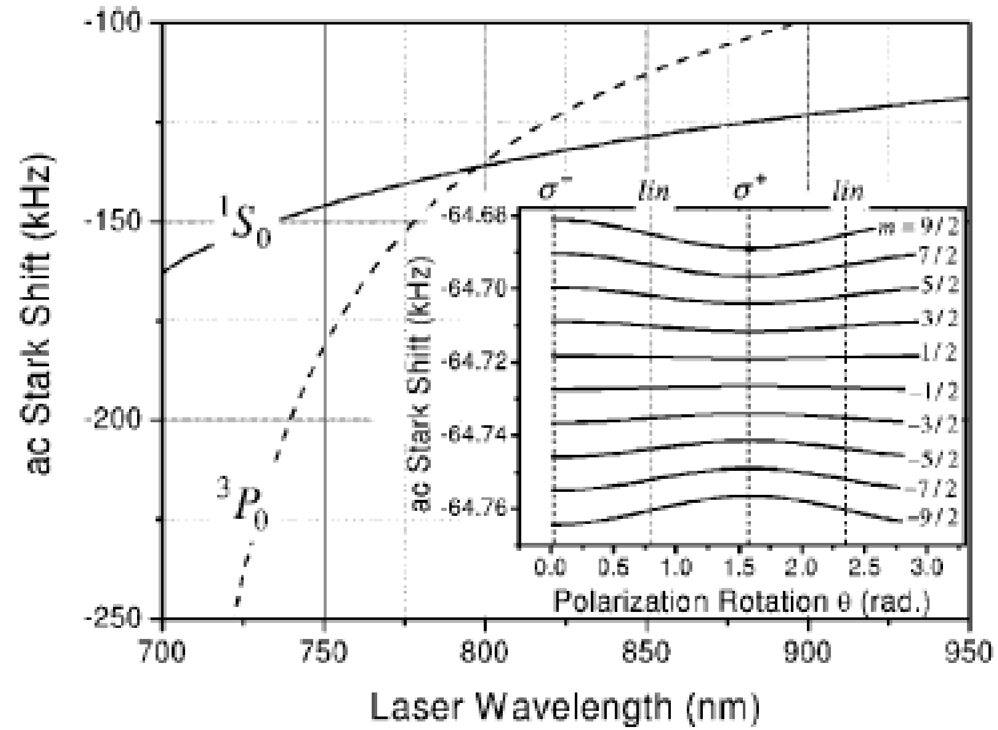
The "Magic" wavelength

- Clever idea (Katori*): Trap atoms in optical lattice at the "magic" wavelength with equal light shift for the upper and lower states of the clock transition: a "stark-free" optical lattice.





- Spectroscopy in tight-confinement (Lamb-Dicke) regime for neutral atoms; Expected to allow for high accuracy

* H. Katori, in *Proc. 6th Symposium Frequency Standards and Metrology*, Ed. P. Gill (World Scientific, Singapore, 2002), pp. 323-330.

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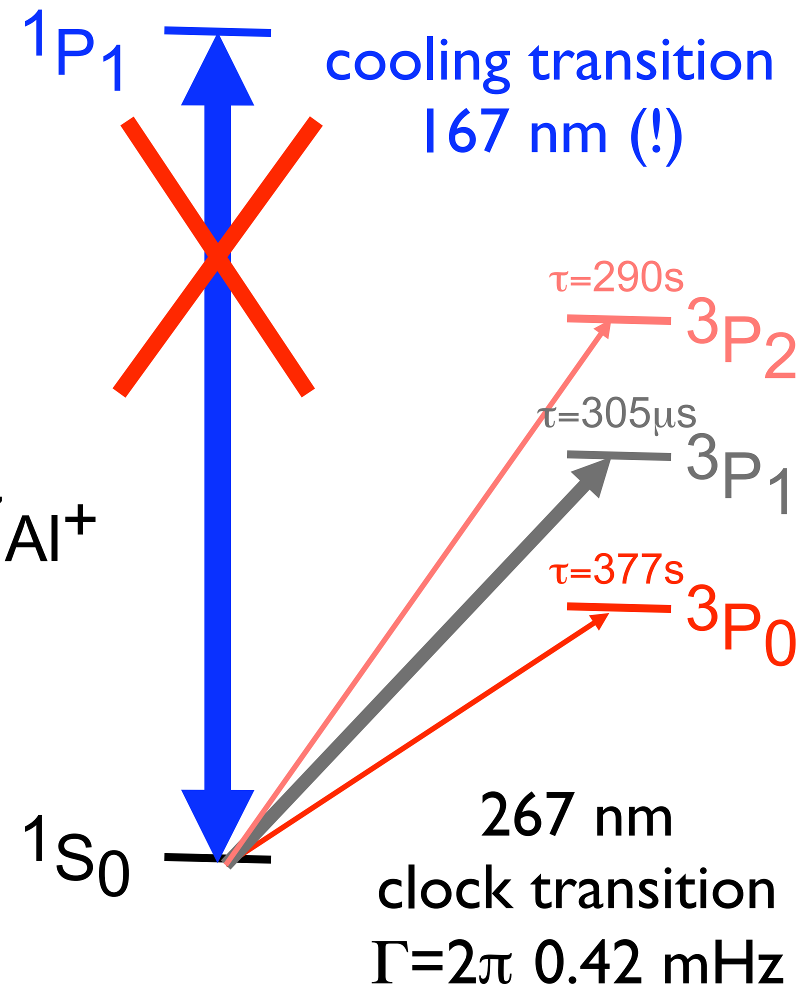
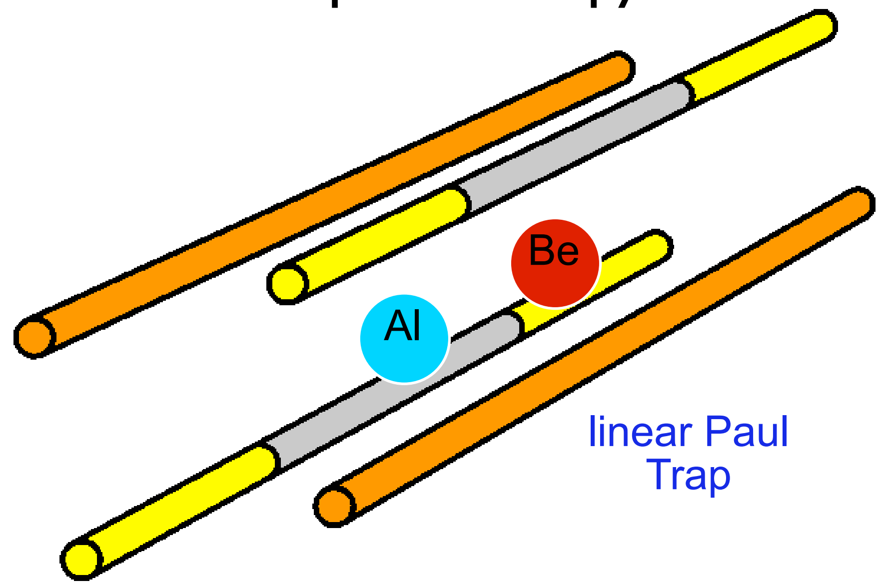
The Al$^+$clock at NIST

Piet Schmidt, Till Rosenband, W. M. Itano, D.J. Wineland, J.C. Bergquist



Clever idea*:
Use quantum logic
for spectroscopy



* D.J. Wineland et al, in *Proc. 6th Symposium Frequency Standards and Metrology*, Ed. P. Gill (World Scientific, Singapore, 2002), pp. 361-367.

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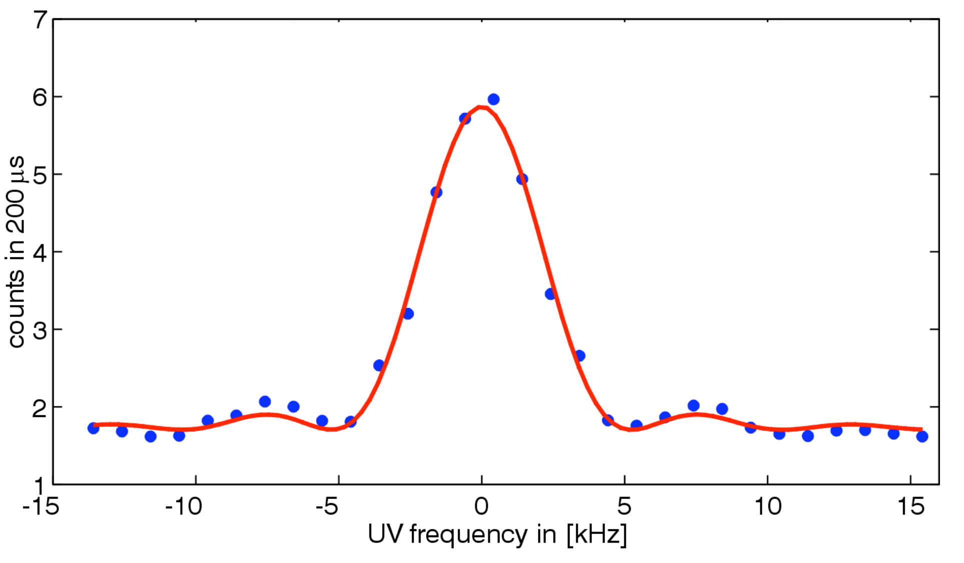
The Al^+ clock at NIST

Clock interrogation cycle:

- Sideband cooling of Be^+ to ground state
- Interrogate Al^+ clock transition
- Map internal state of Al^+ ion onto motional mode
- Map motional mode onto Be^+ internal state
- Read out Be^+ internal state

$$^1S_0 \leftrightarrow {}^3P_1\ F = 7/2$$

Technique has been recently demonstrated on both wide and narrow Al transitions



Optical standard candidates*

Ion	λ	$\Delta\nu$	Groups*
Sr^+	674 nm	0.4 Hz	NPL, NRC
In^+	236 nm	0.82 Hz	MPQ
Hg^+	282 nm	6.7 Hz	NIST
Al^+	267 nm	1 mHz	NIST
Yb^+	436 nm (*S*-*D*)	3.1 Hz	PTB
Yb^+	467 nm (*S*-*F*)	1 nHz	NPL

Atom	λ	$\Delta\nu$	Groups*
Sr	698 nm	10 mHz	Tokyo, JILA, SYRTE
Ca	657 nm	470 Hz	NIST, PTB
Yb	578 nm	50 mHz	NIST, UW

*non-exhaustive list

Optical clock expectations

		Ultimate limits:
Cold atoms	Calcium	High stability expected
	Single ion clocks	High accuracy, moderate stability expected
Tight confinement	Optical lattice clocks	High accuracy and stability expected

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Applications of atomic clocks

- Precision Measurement
  - The second can be implemented more accurately than any other SI base unit
    - Commercial clock can measure frequency to 10^{-12} in 1 s
    - Always try to cast measurements into frequency
  - Meter defined in terms of second
  - "Practical" standards for volt (Josephson voltage h/2e), and ohm (quantum hall resistance h/e^2) depend on second
    - Implies "practical" ampere, kilogram based upon second
  - Other base units (candela, mole, kelvin) independent, cannot be measured precisely

Applications of atomic clocks

- Navigation and positioning:
  Satellite navigation and ranging; GPS, etc.

- Communication
  - Network synchronization
  - High-speed communication

- Astronomy
  - Very long baseline interferometry (VLBI)

- Fundamental tests
  - High-resolution spectroscopy
  - Astronomical relativity tests possible through VLBI
  - Tests of quantum mechanics
  - Equivalence principle, relativity
  - Stability of fundamental constants

Partial error budget for NIST-F1 cesium fountain

Physical effect	Bias magnitude $/10^{-15}$	Type B uncertainty $/10^{-15}$
Second-order (quadratic) Zeeman	+44.76	0.3
Second-order Doppler	< 0.1	< 0.1
Cavity pulling	< 0.1	< 0.1
Rabi pulling	< 0.1	< 0.1
Cavity phase (distributed)	< 0.1	< 0.1
Fluorescent light shift	< 0.1	< 0.1
Adjacent atomic transitions	< 0.1	< 0.1
Spin exchange	0.0*(0.7 to 7.8)	0.84
Black body	−20.6	0.3
Gravitation	+180.54	0.1

From S. R. Jefferts et al., Metrologia, **39**, 321-336 (2002).

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Stability of fundamental constants

Atomic clocks measure transition frequencies that generally depend upon a combination of fundamental constants.

- Some "historical" records to document values of fundamental constants in earlier universe:

    – Quasar absorption spectra at high redshift
    – Isotope ratios at Oklo fossil reactors

- Interpretation of data is model dependent;
  May indicate value of the fine structure constant $\alpha = e^2/\hbar c$ in earlier universe

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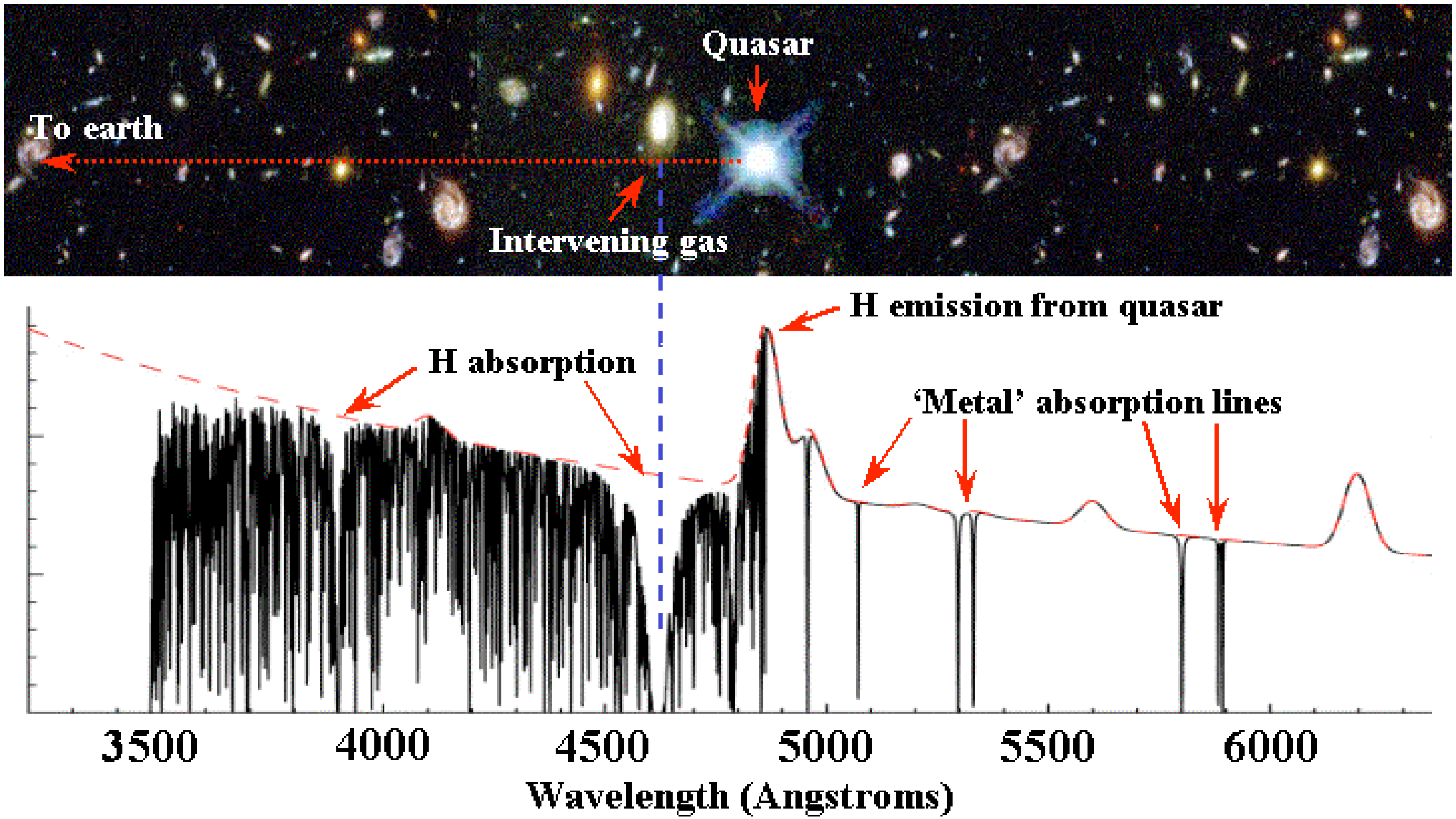
Quasar absorption spectra



- Compare "metal" absorption lines to those measured in laboratory. (Precise laboratory values need work!)

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Fossil reactors at Oklo

"The impression has been given that to design and construct a nuclear reactor is a feat unique to physical science and engineering creativity. It is chastening to find that, in the Proterozoic, an unassertive community of modest bacteria built a set of nuclear reactors that ran for millions of years."

– *From James Lovelock, The Ages of Gaia (1988)*

Remains of Oklo reactor core # 15, 1.5 billion years old

Stability of fundamental constants

	Yes, α has changed.	No, α has not changed
Oklo data 10^9 yr	$\Delta\alpha(\text{past})/\alpha = +(4.5 \pm 1.5) \times 10^{-8}$ S. K. Lamoreaux and J. R. Torgerson, Phys. Rev. D **69** 121701 (2004).	$\Delta\alpha(\text{past})/\alpha = -(0.36 \pm 1.44) \times 10^{-8}$ Y. Fujii, et al., Nuc. Phys. B **573**, 377 (2000).
Quasar data 10^{10} yr	$\Delta\alpha(\text{past})/\alpha = -(0.54 \pm 0.12) \times 10^{-5}$ M.T. Murphy, et al., astro-ph/0306483.	$\Delta\alpha(\text{past})/\alpha = -(6 \pm 6) \times 10^{-7}$ R. Srianand, et al, Phys. Rev. Lett. **92** 121302 (2004).

- Clock comparisons may provide the best test of *present-day* changes in physical constants.

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Conclusions for Part I

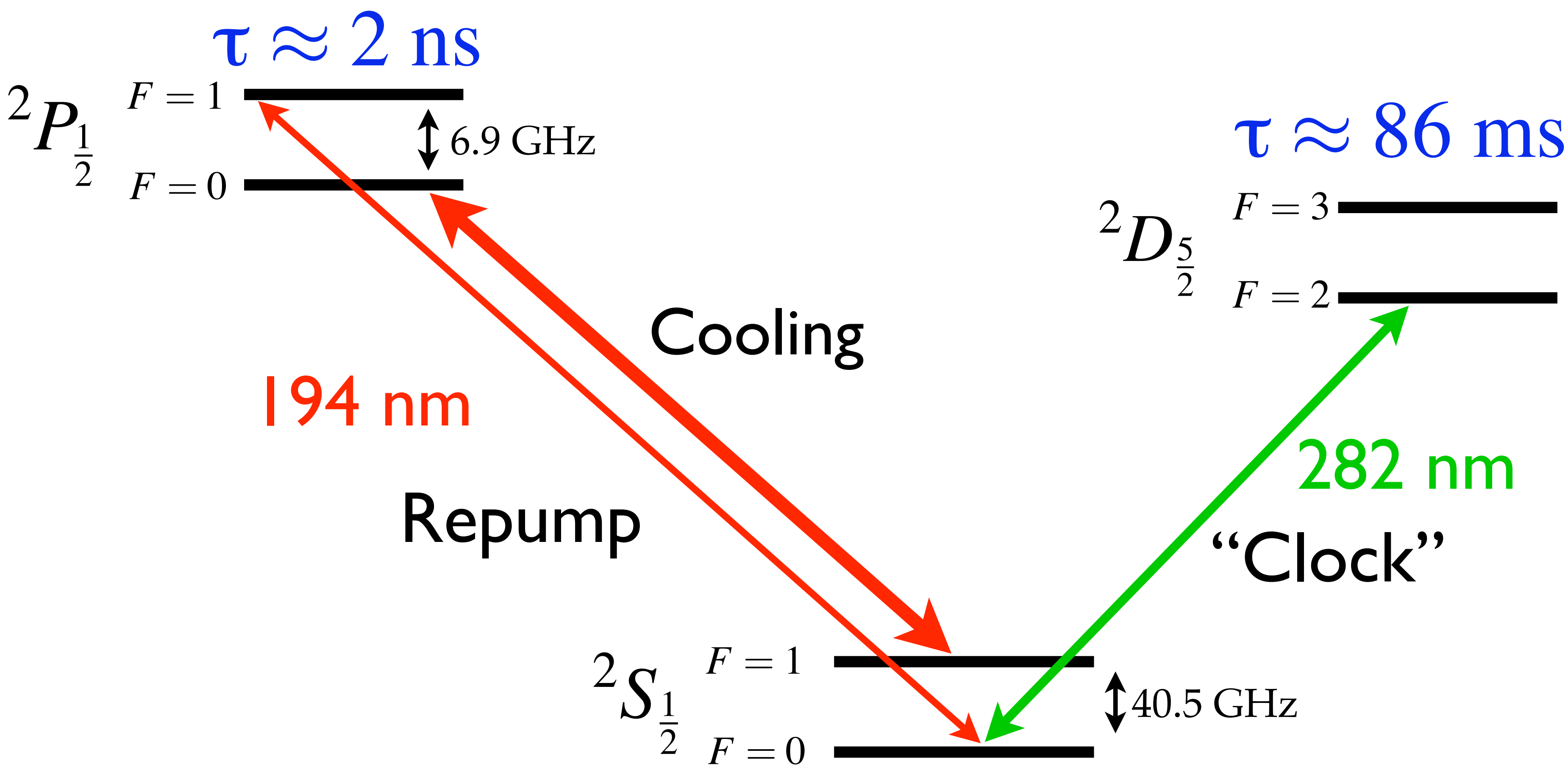
- The transition from microwave to optical transitions is facilitating a revolution in frequency standards

- New techniques in several areas are expected to lead to high accuracy, with wide benefits

Part II: the mercury ion clock

- An atomic clock based upon an optical transition in a single ion of mercury

$^{199}Hg^{+}$ Energy Levels



- Atomic line $Q \approx 1.5 \times 10^{14}$

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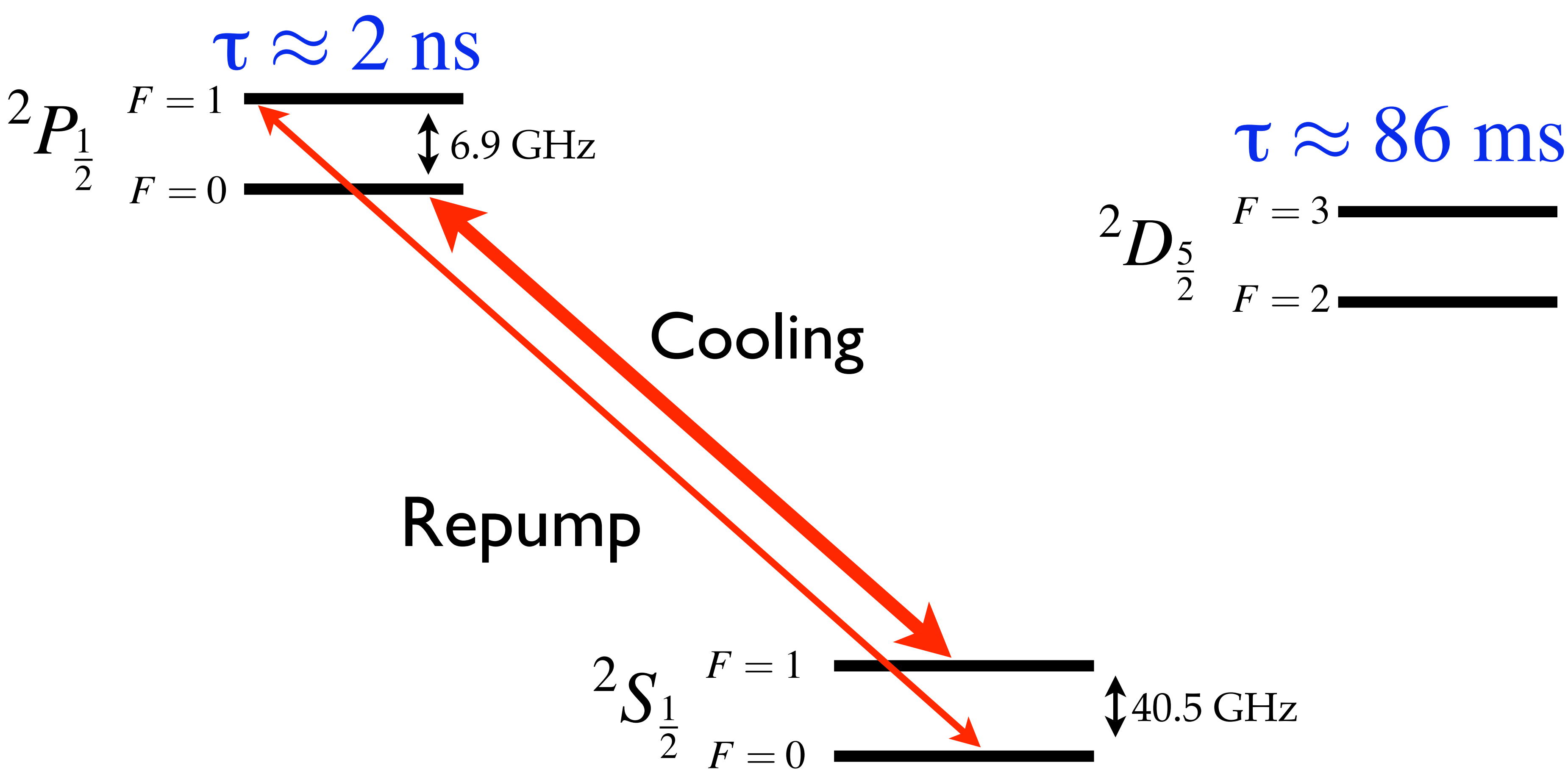
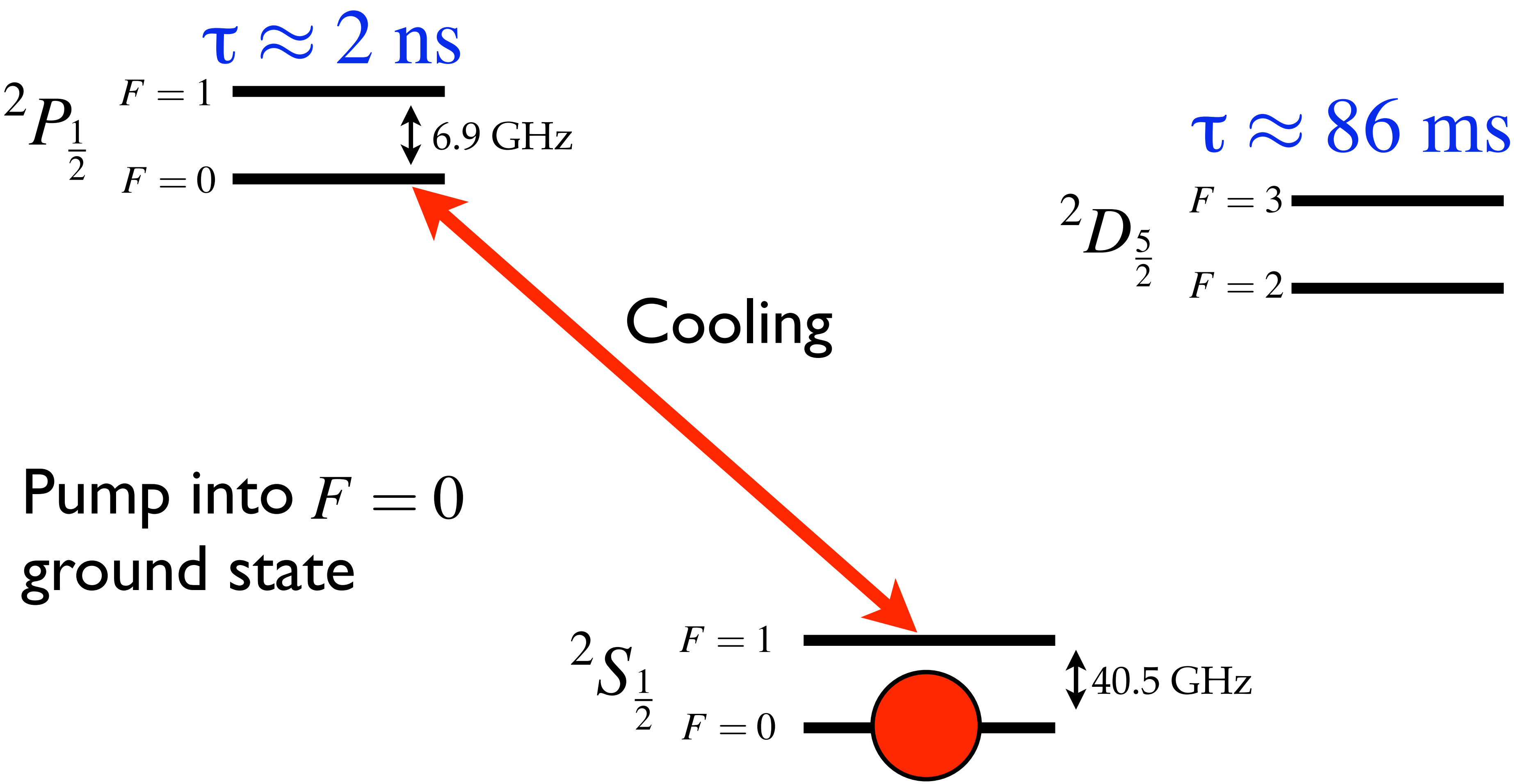
Quantum Jump Spectroscopy



- State detection by electron shelving

H.G. Dehmelt, *Bull. Am. Phys. Soc.* **20**, 60 (1975).

Quantum Jump Spectroscopy



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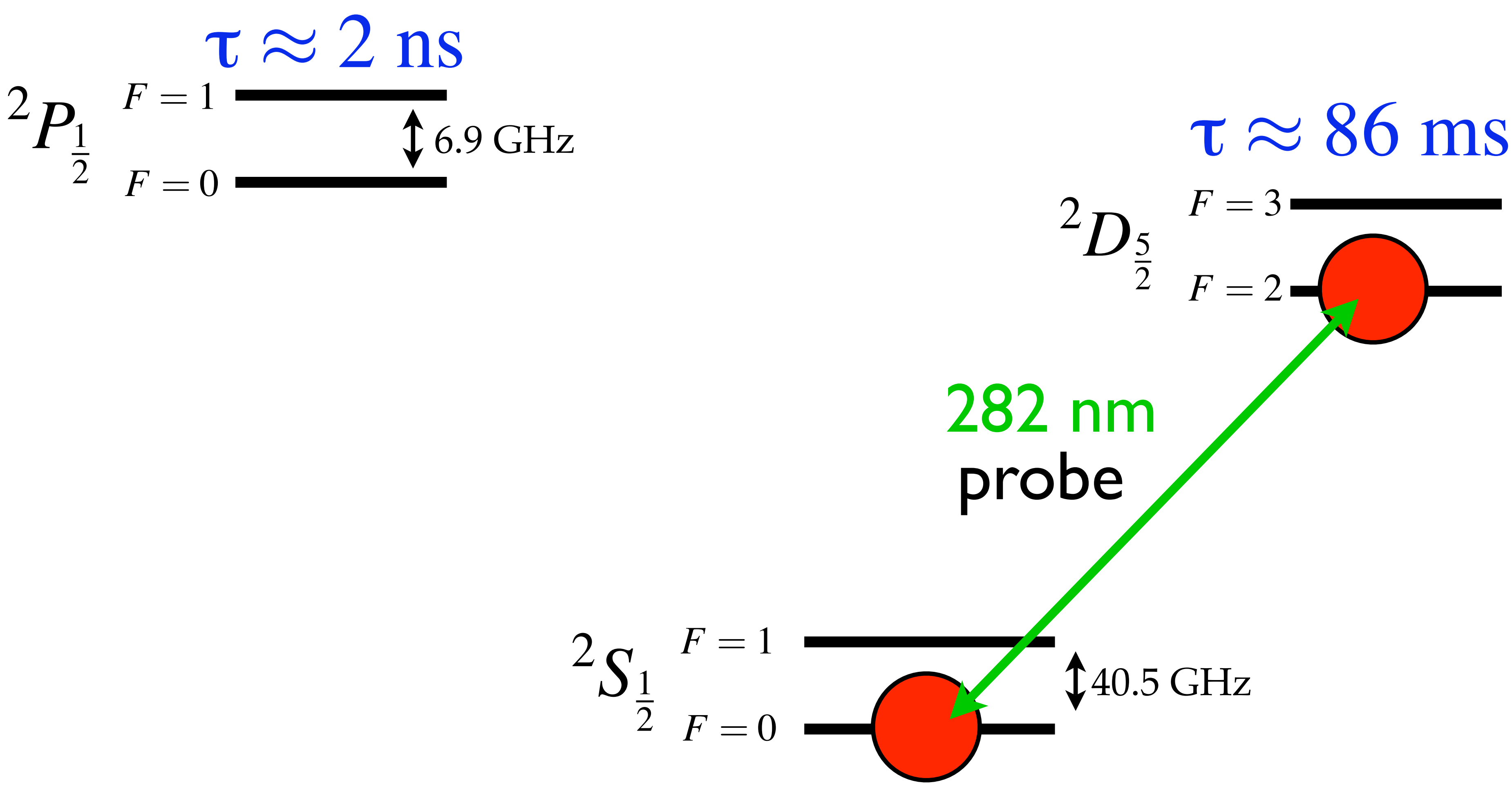

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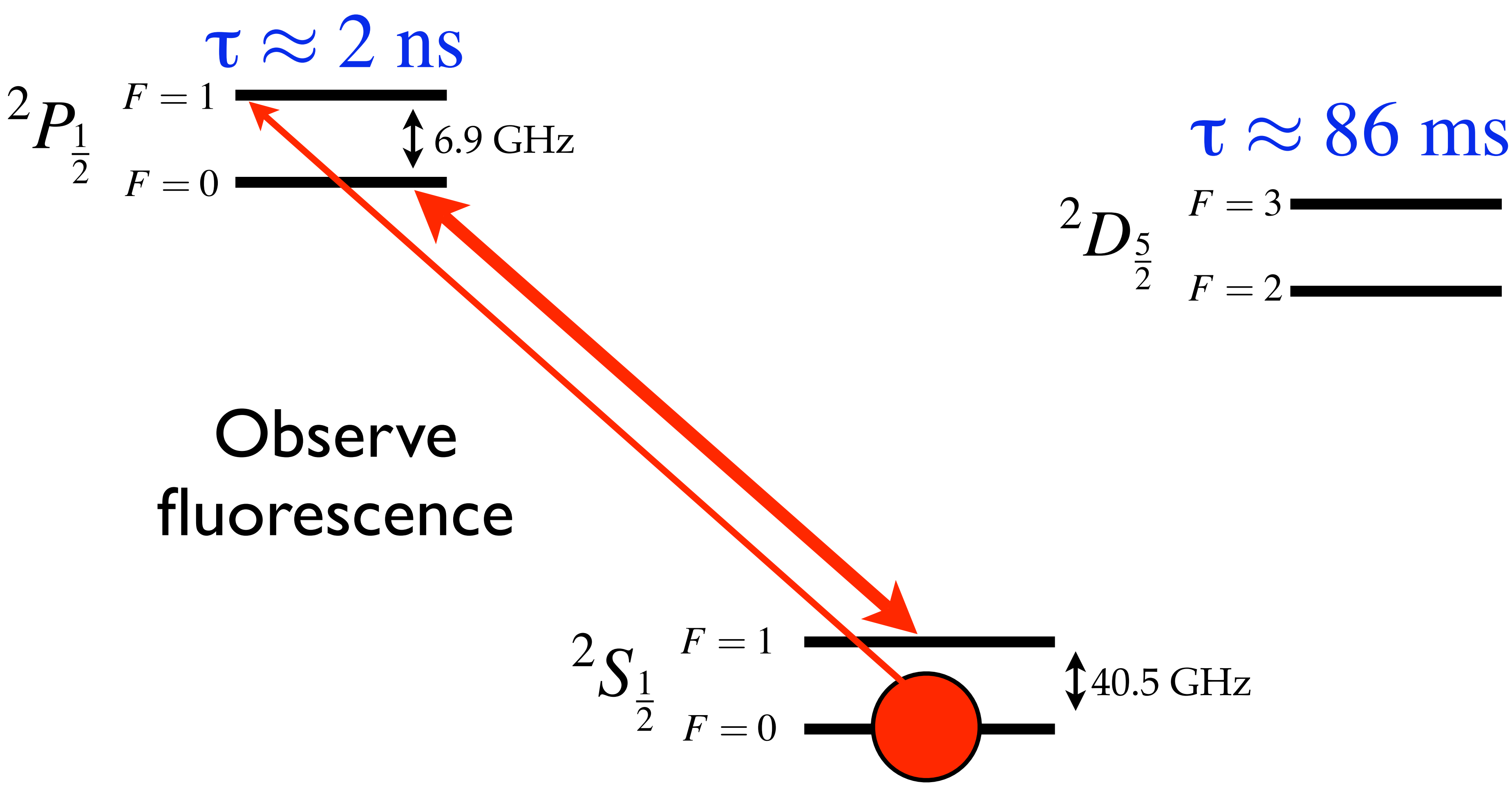

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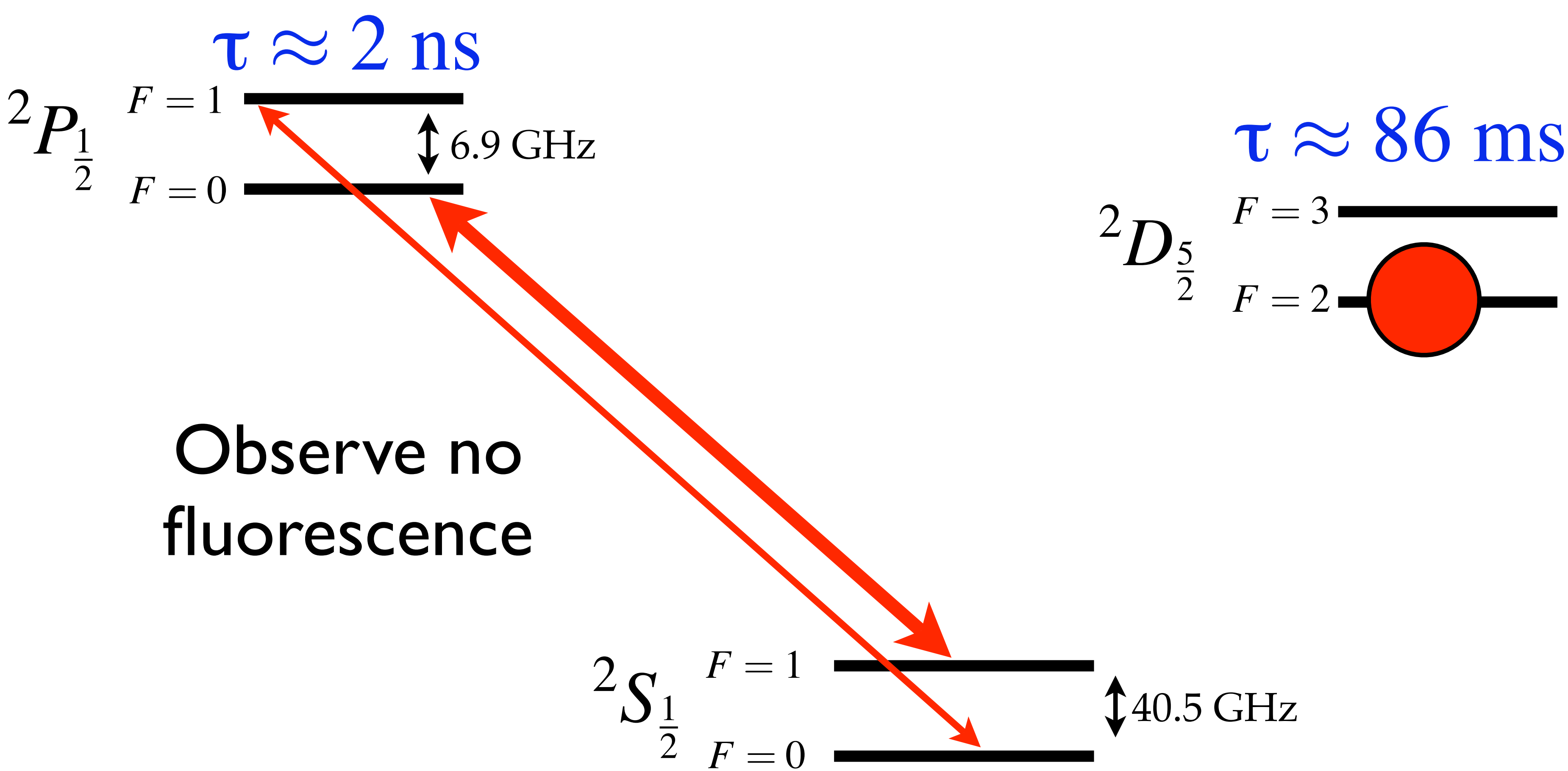
Quantum Jump Spectroscopy



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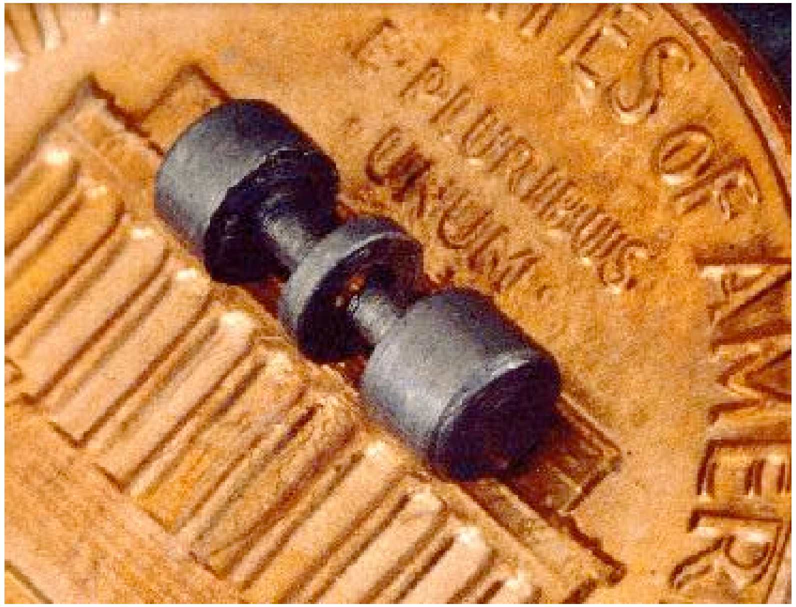
Cryogenic Spherical Paul Trap



- Trap storage time: months (in principle)
- High environmental isolation
  (collision rate, blackbody)

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Cryogenic trap system

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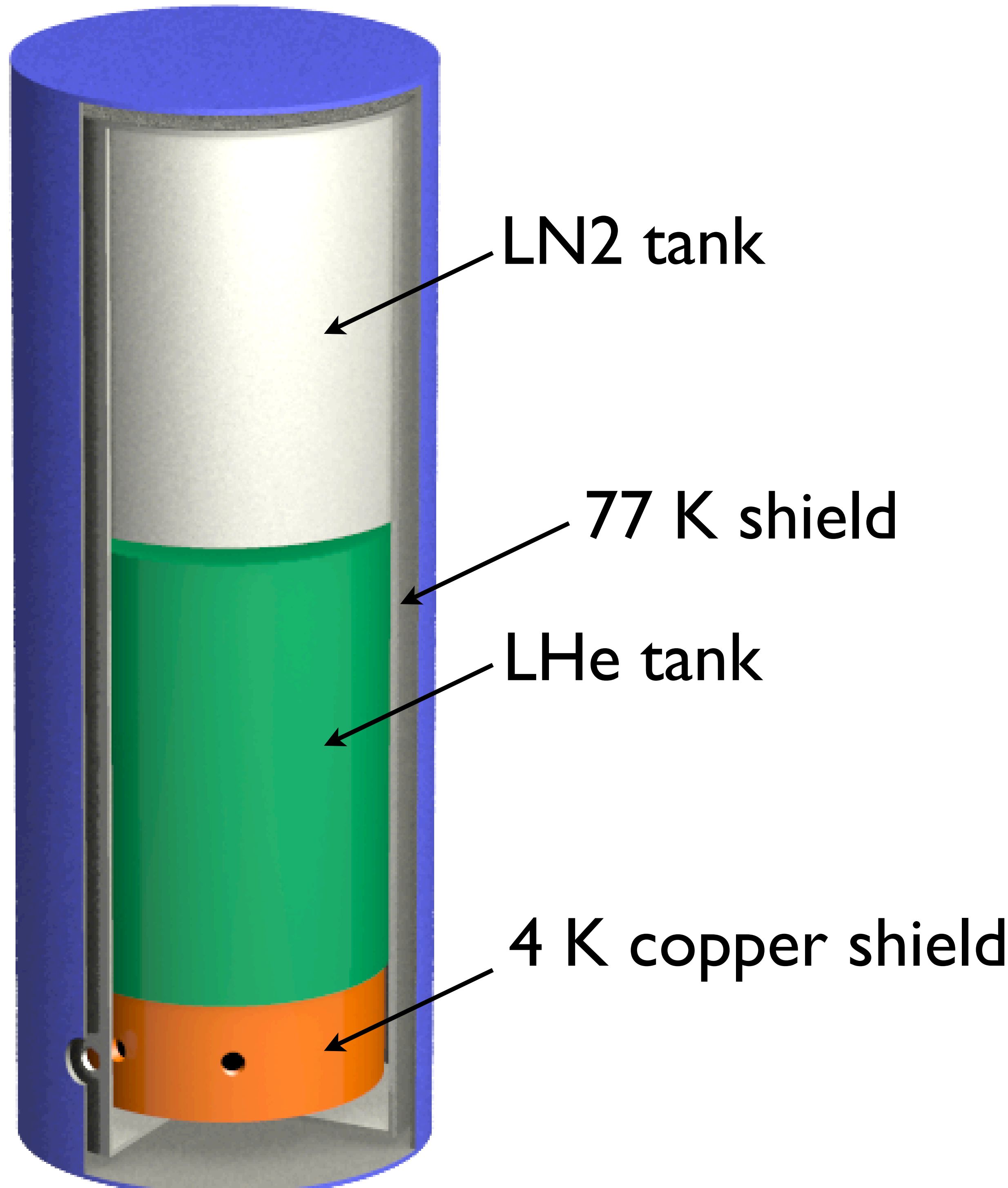
Cryogenic trap system



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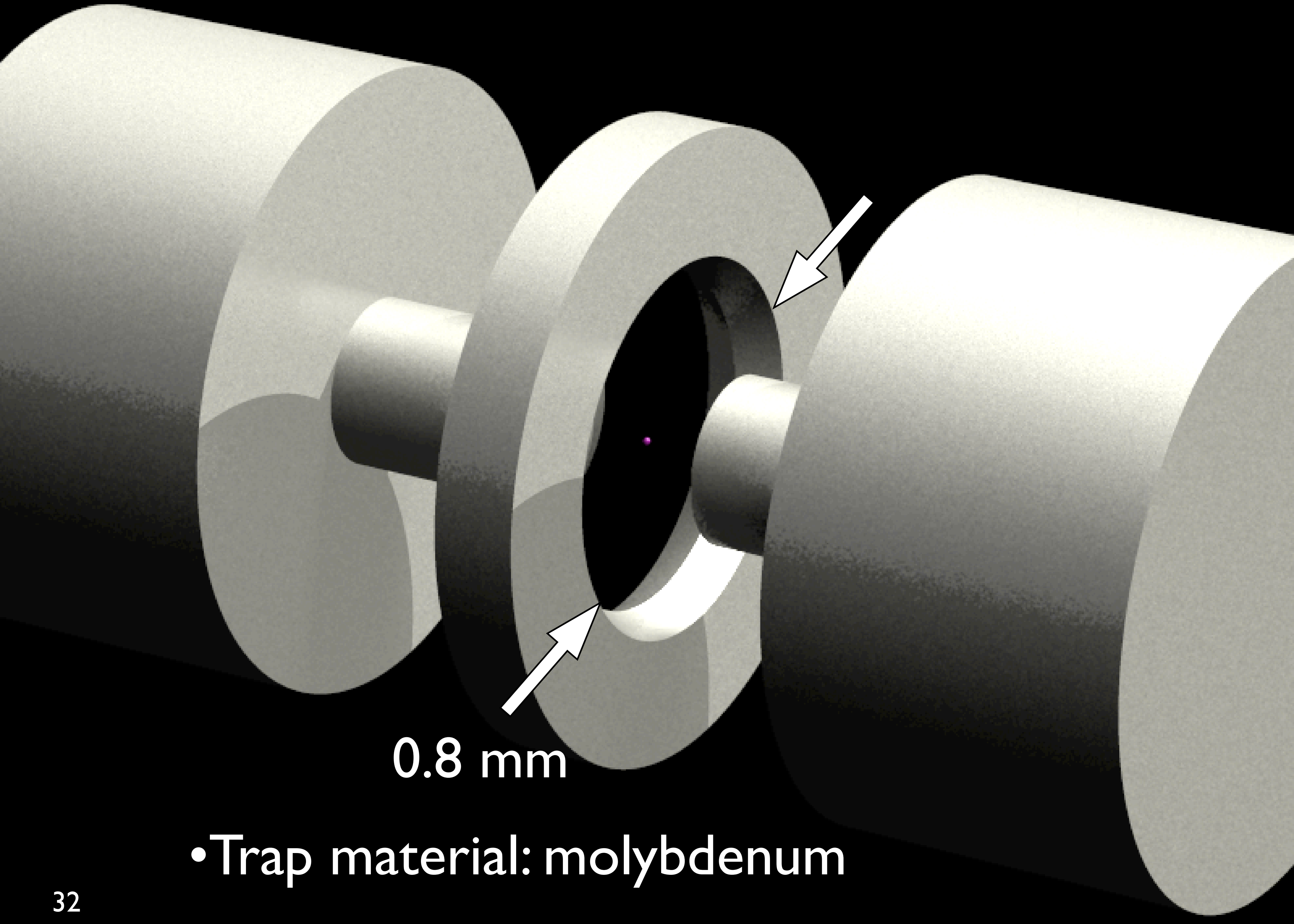
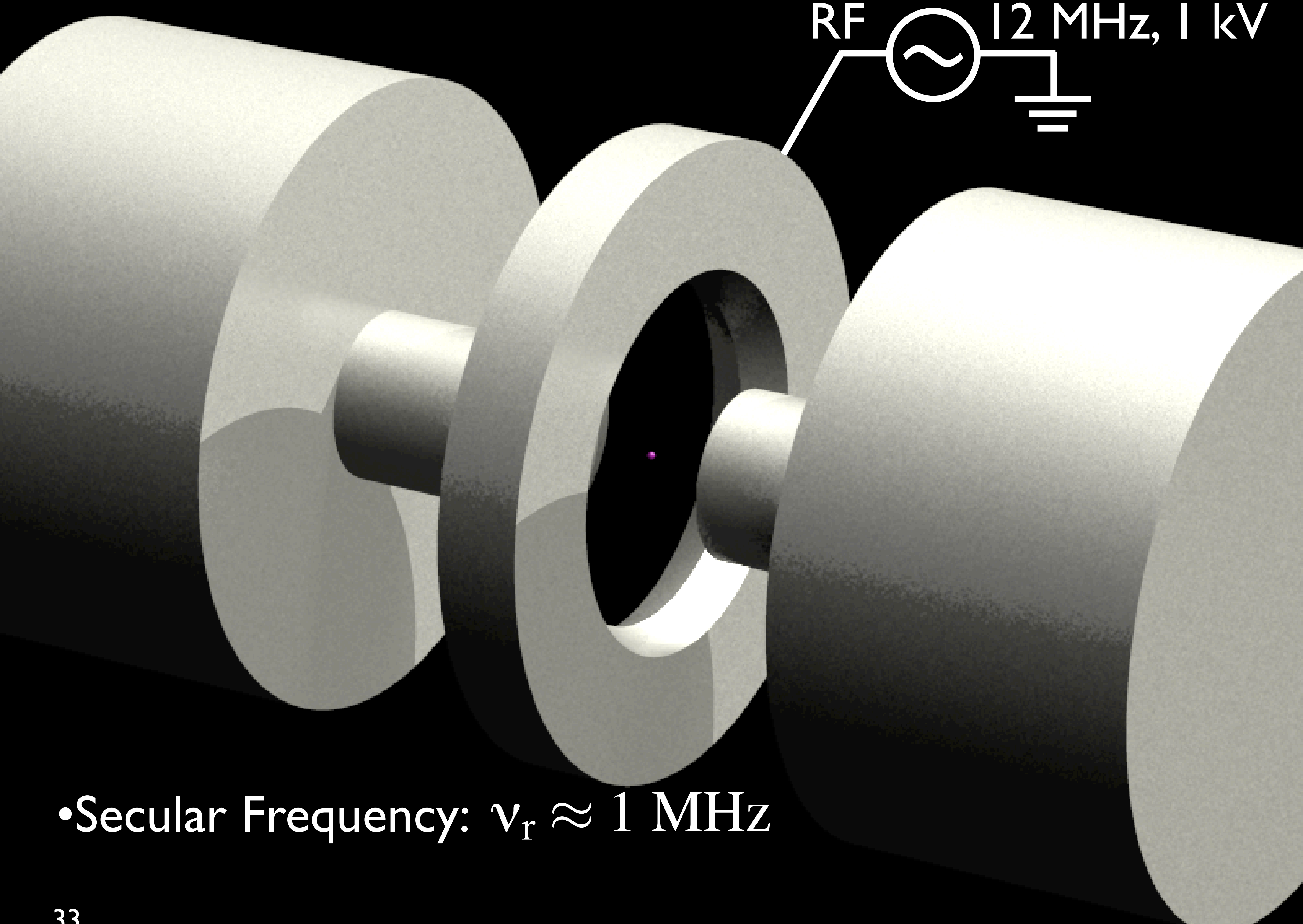
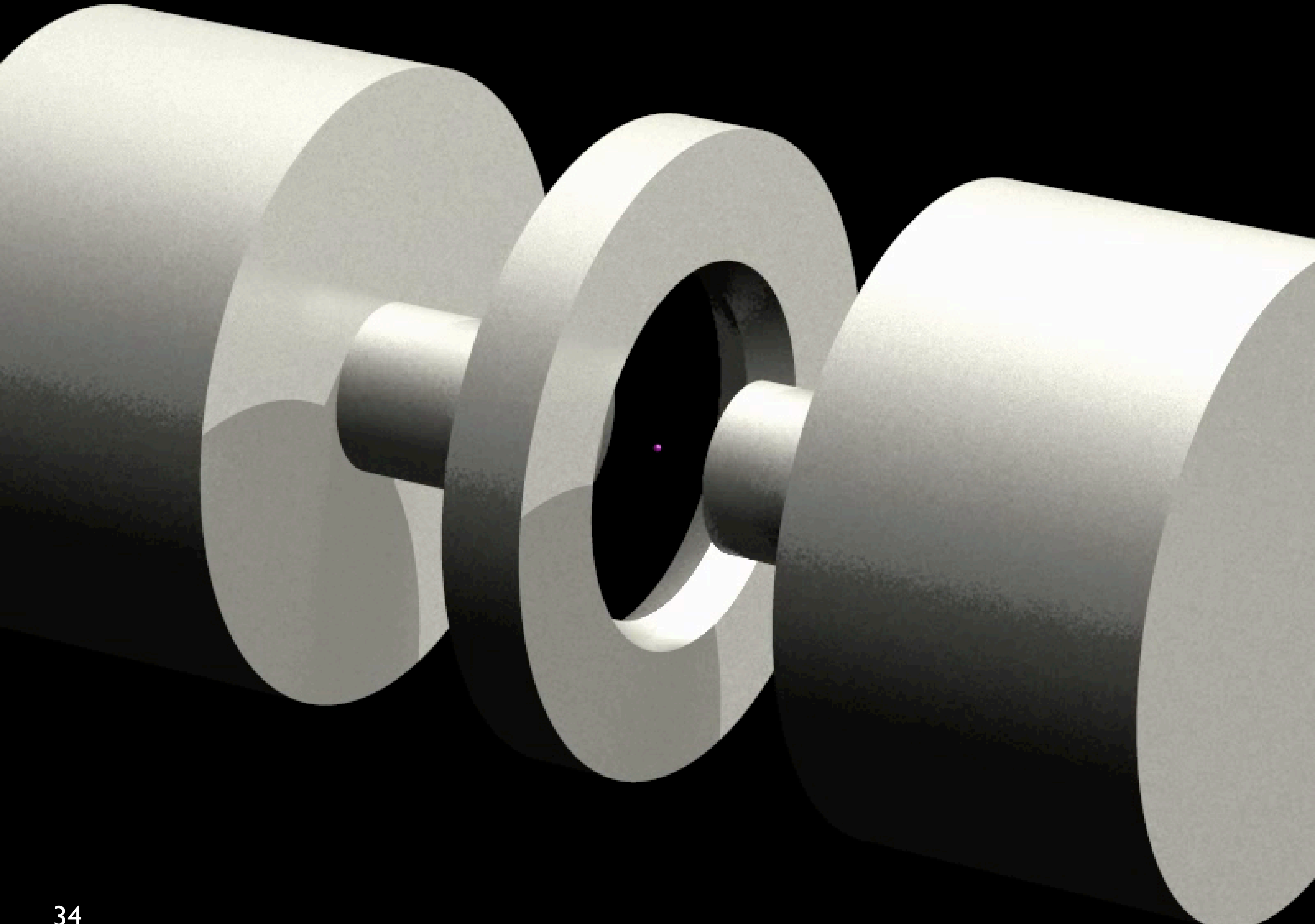
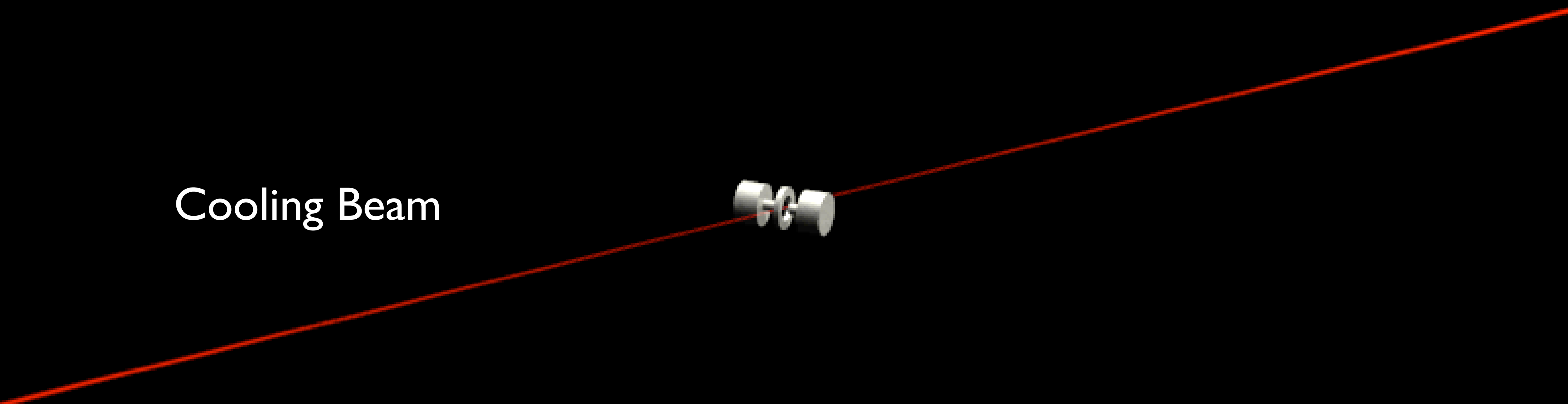


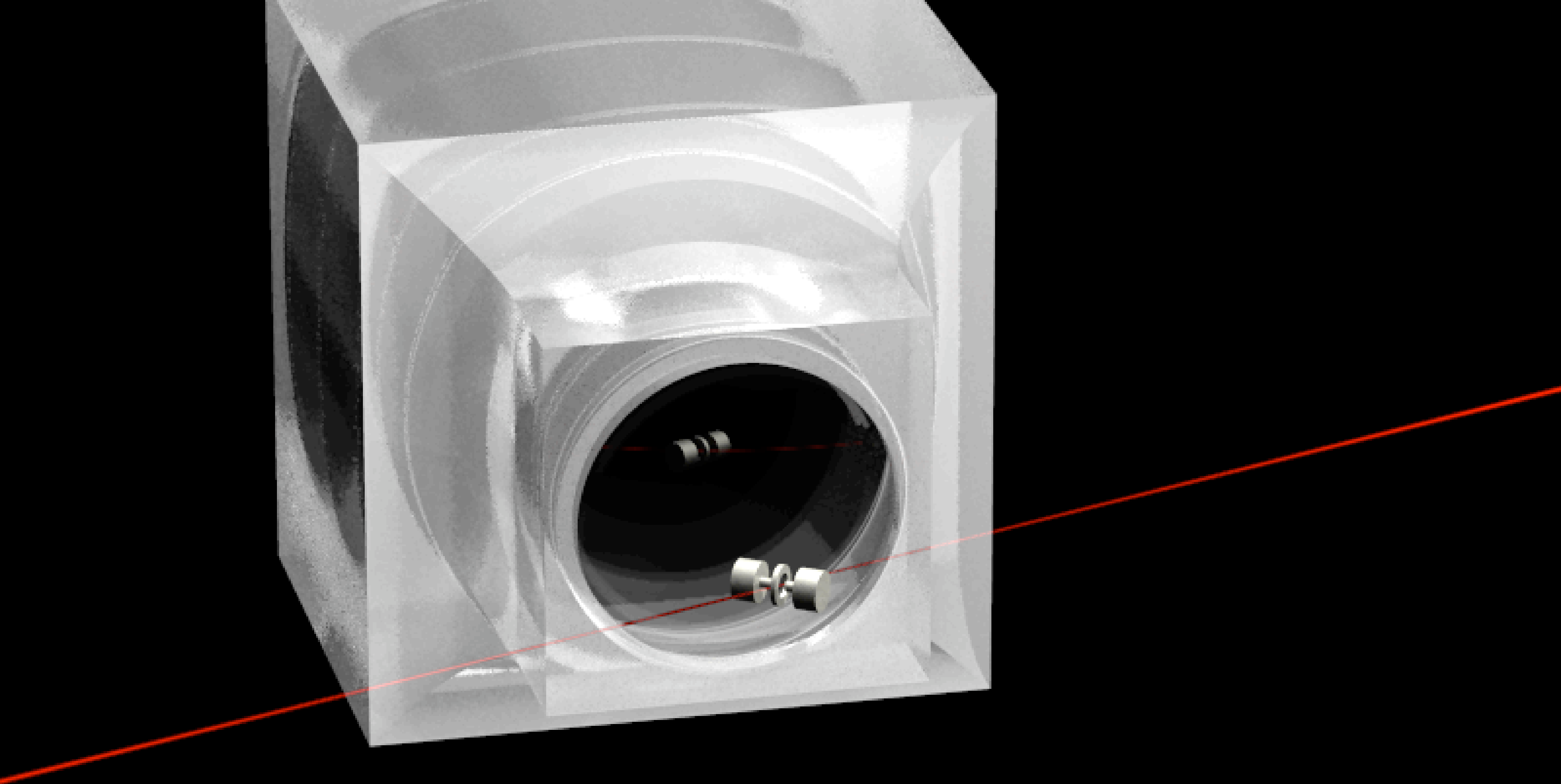
- Trap material: molybdenum



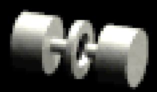
•Secular Frequency: $\nu_r \approx 1$ MHz

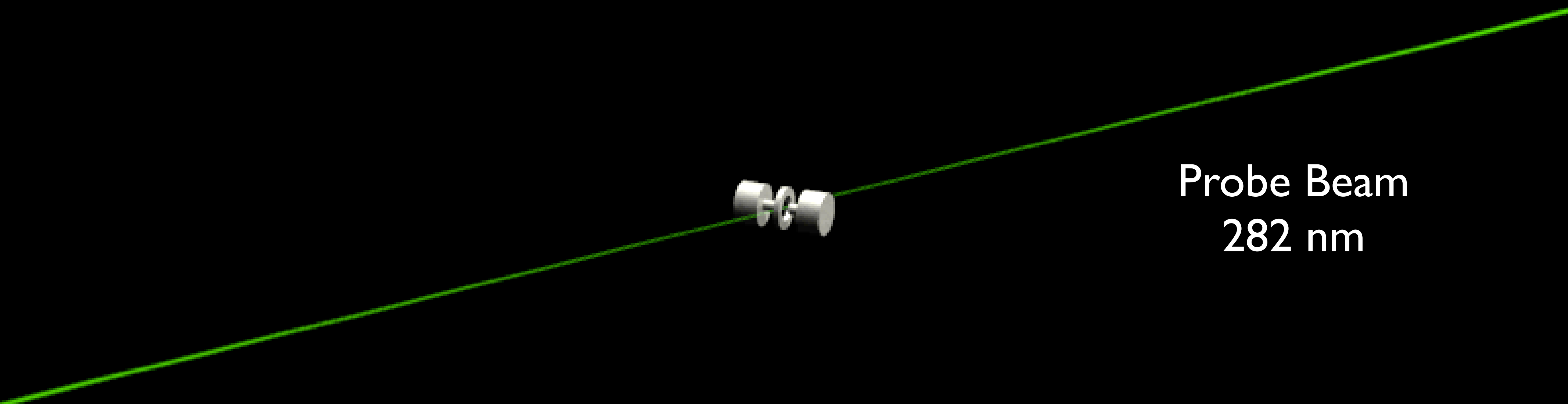



Cooling Beam

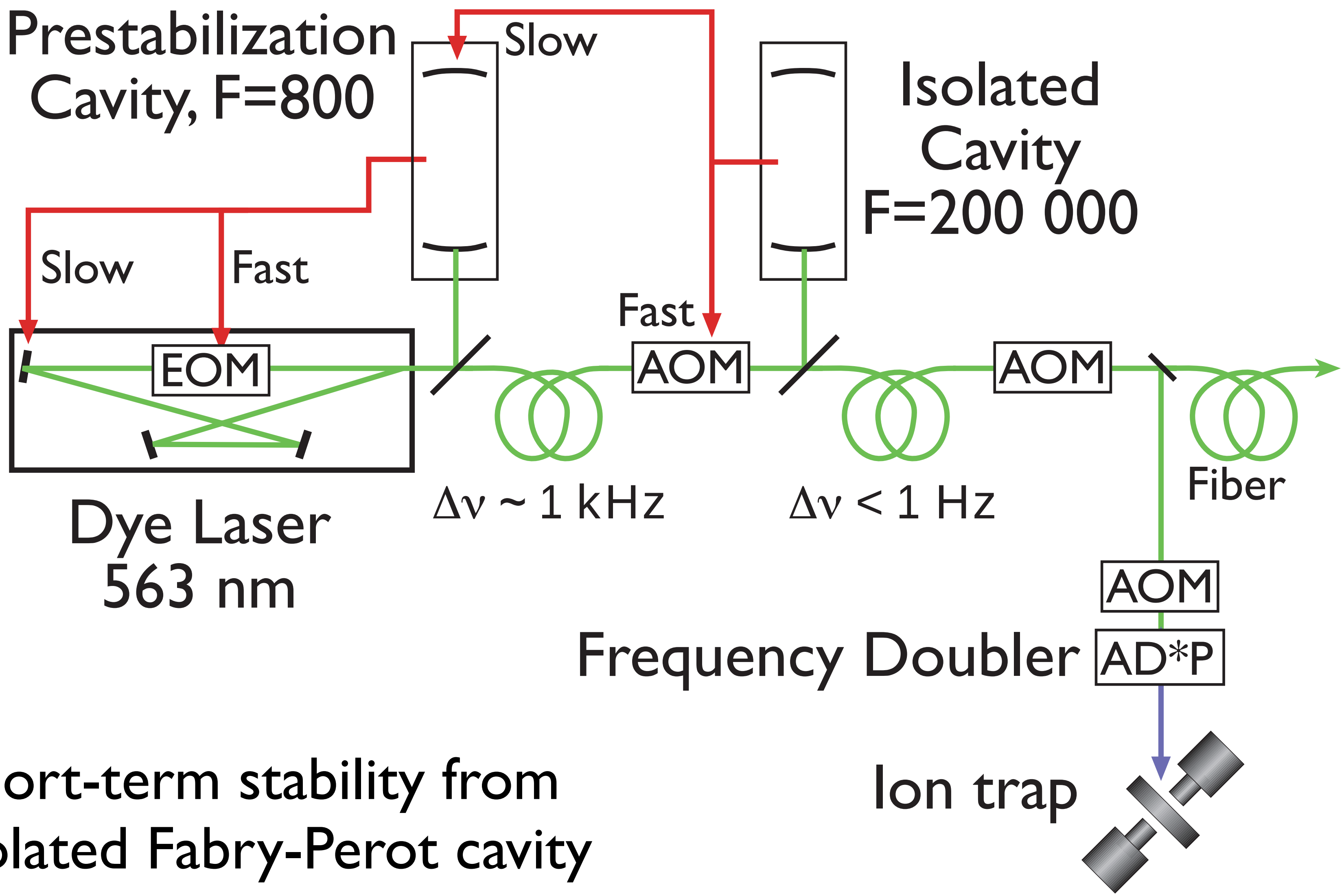


Fused silica lens in cryostat
for state detection




Probe Beam
282 nm

Stable 282 nm light source



- Short-term stability from isolated Fabry-Perot cavity
- Long-term stability from ion

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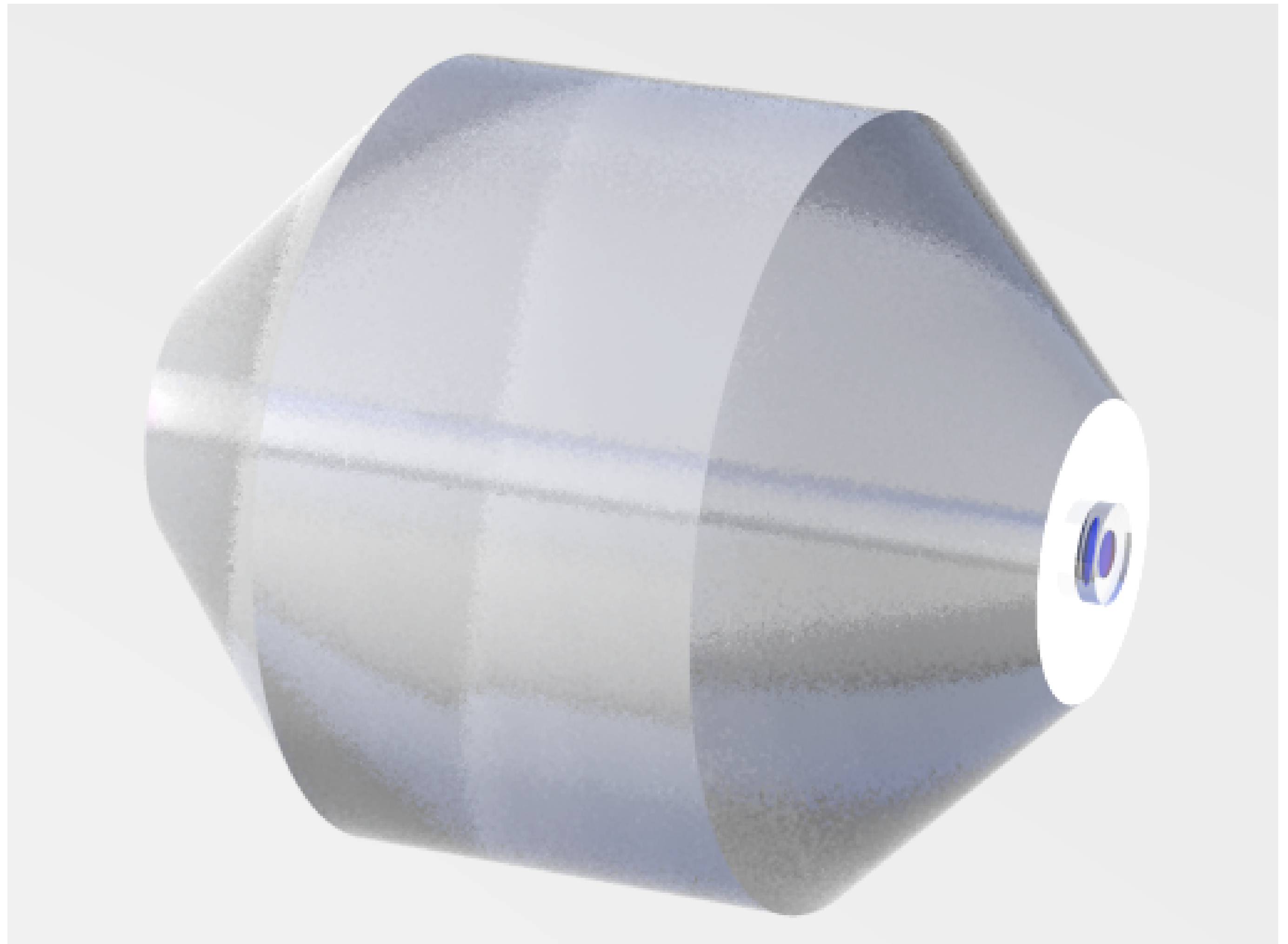
Isolated Cavities

- ULE Spacer
  25 cm
- $F \approx 200\ 000$



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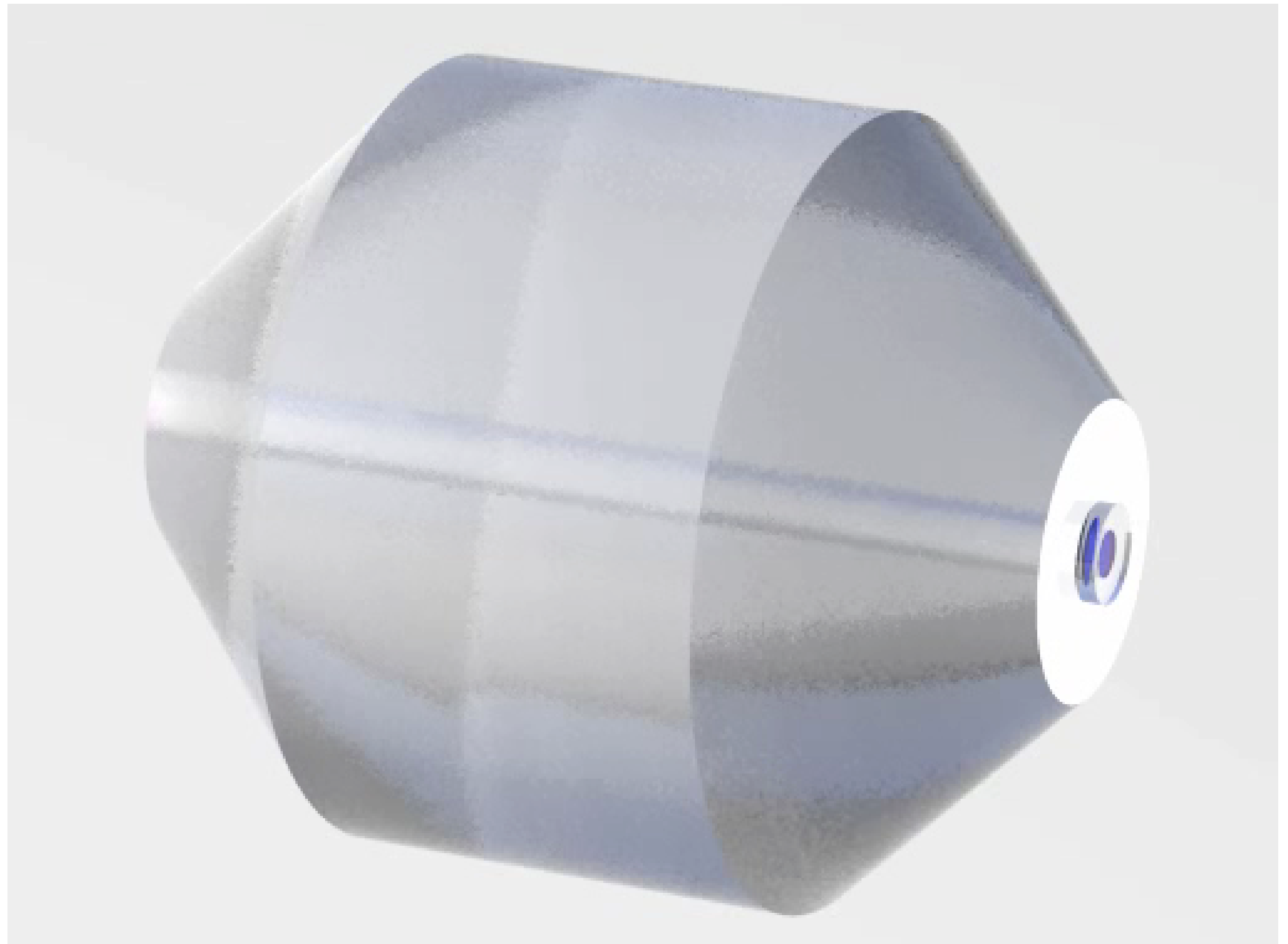

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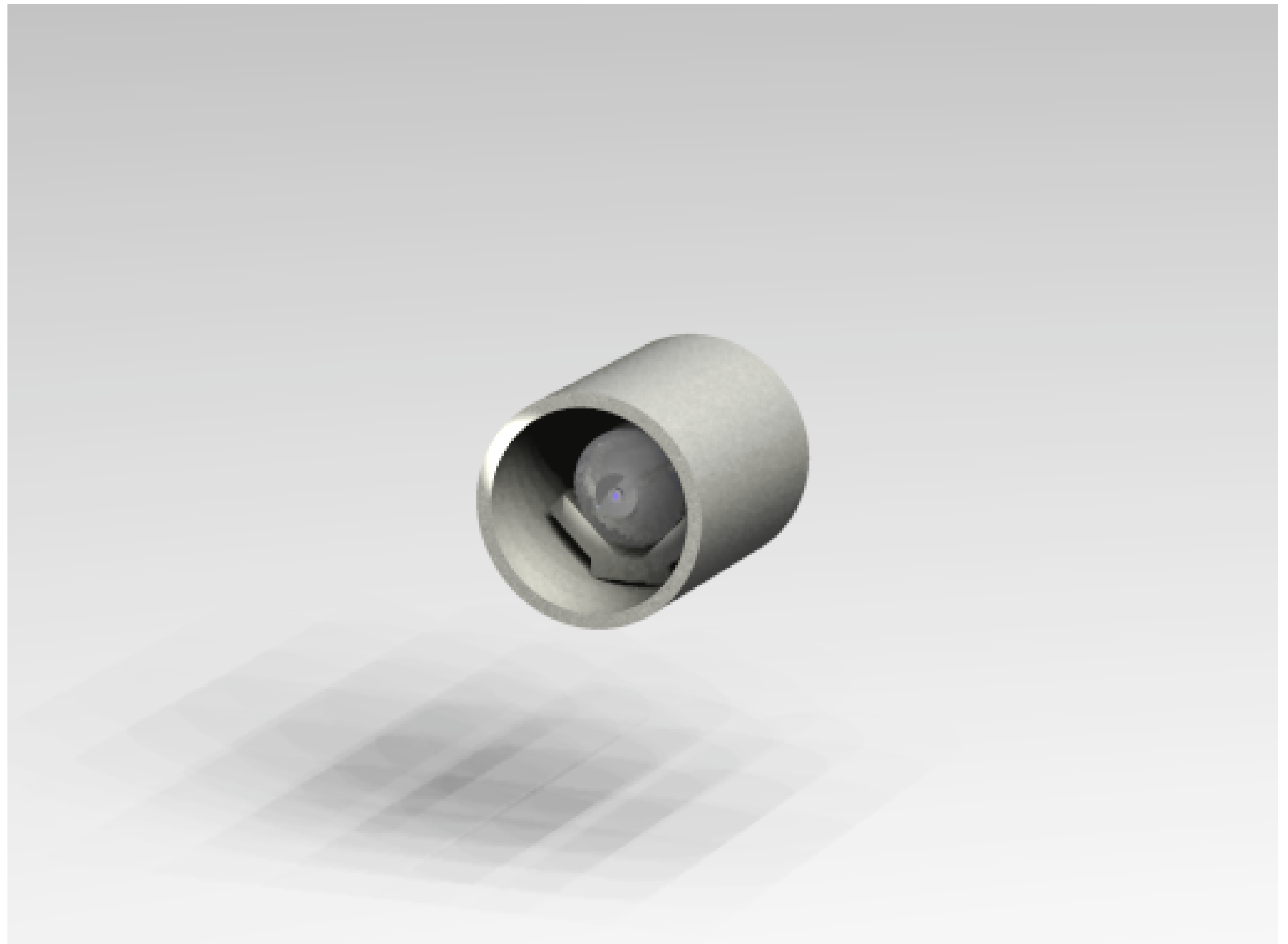

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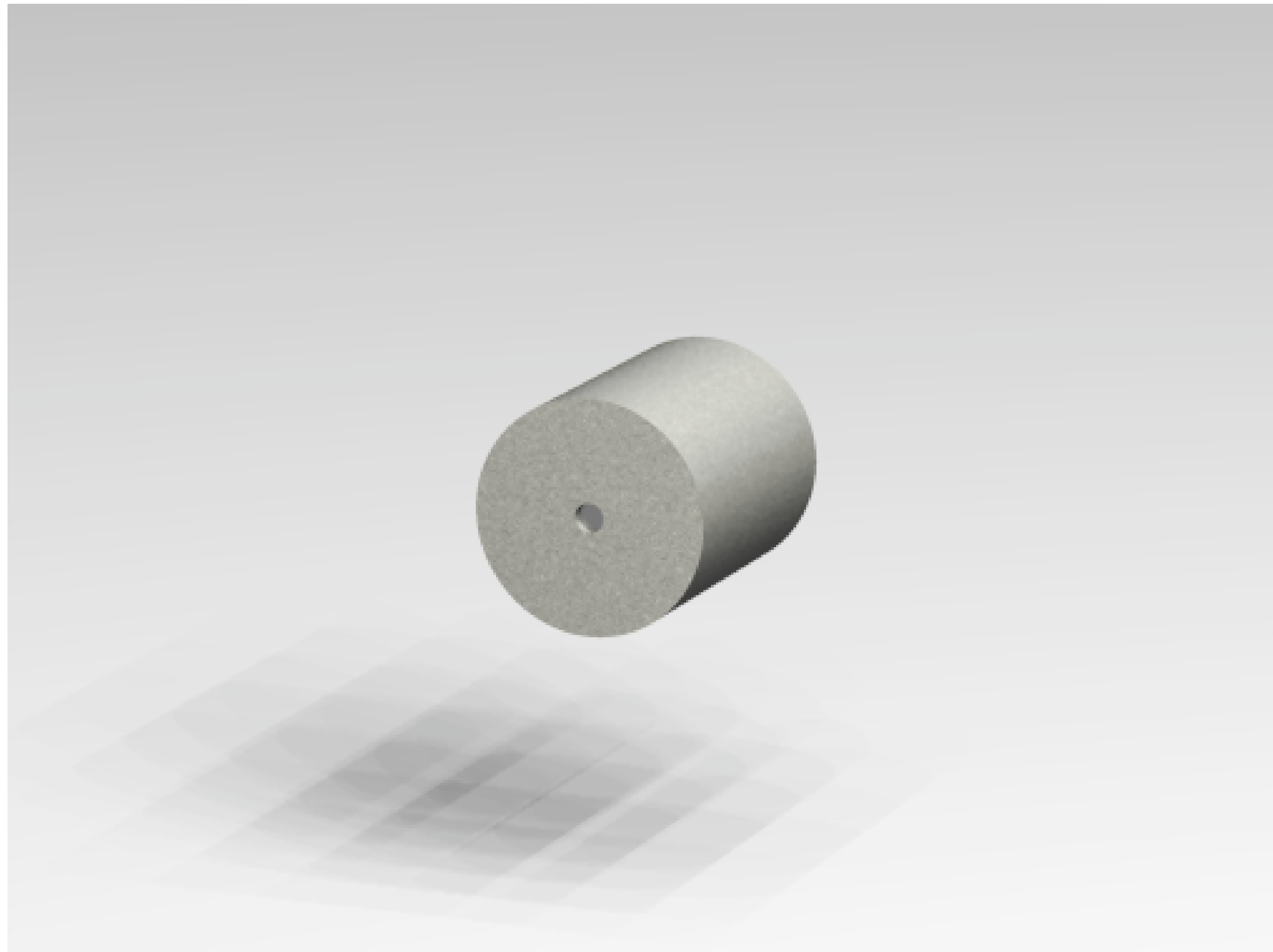

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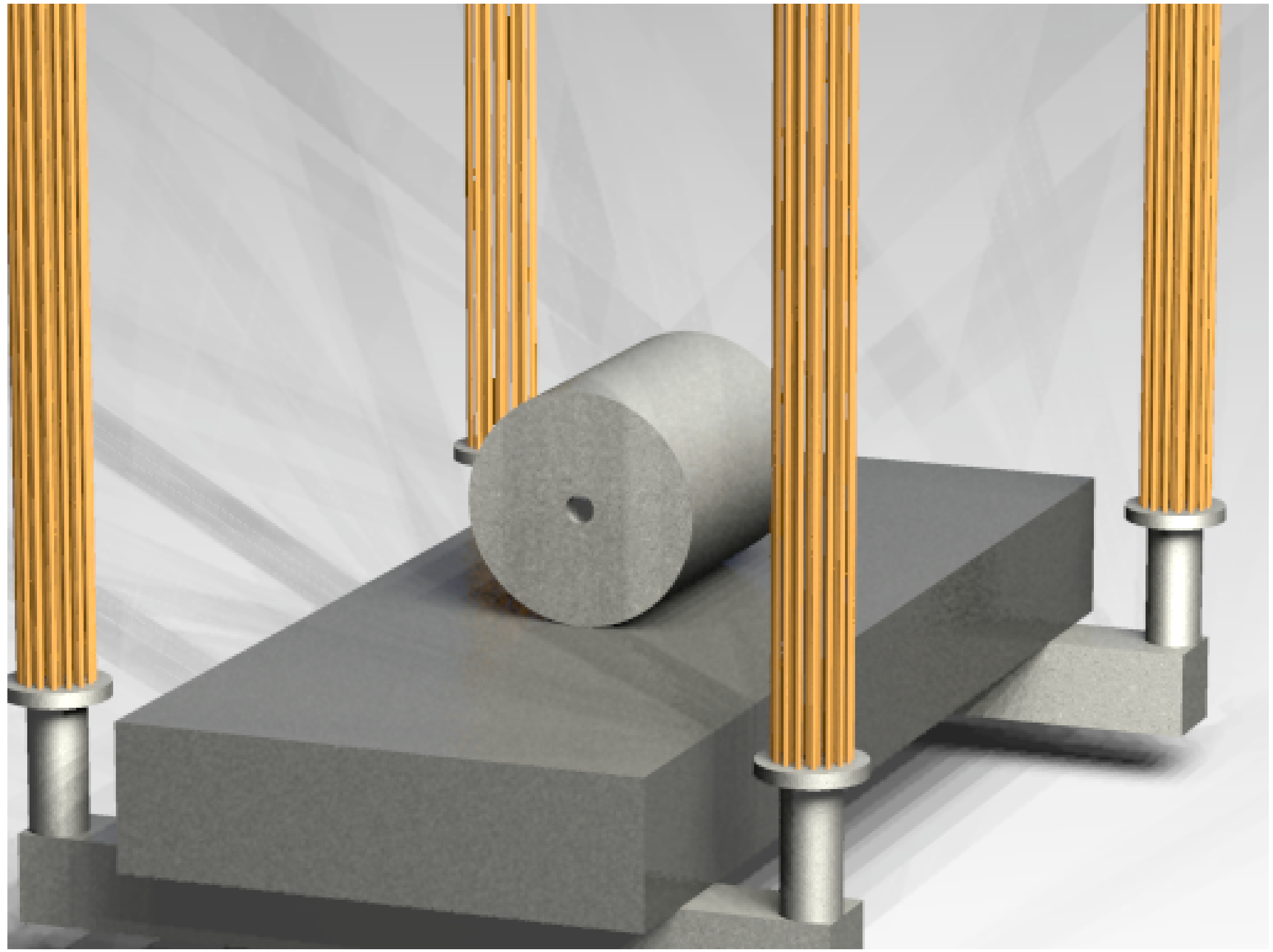
Isolated Cavities

- ULE Spacer
  25 cm
- $F \approx 200\,000$
- Thermal and seismic isolation



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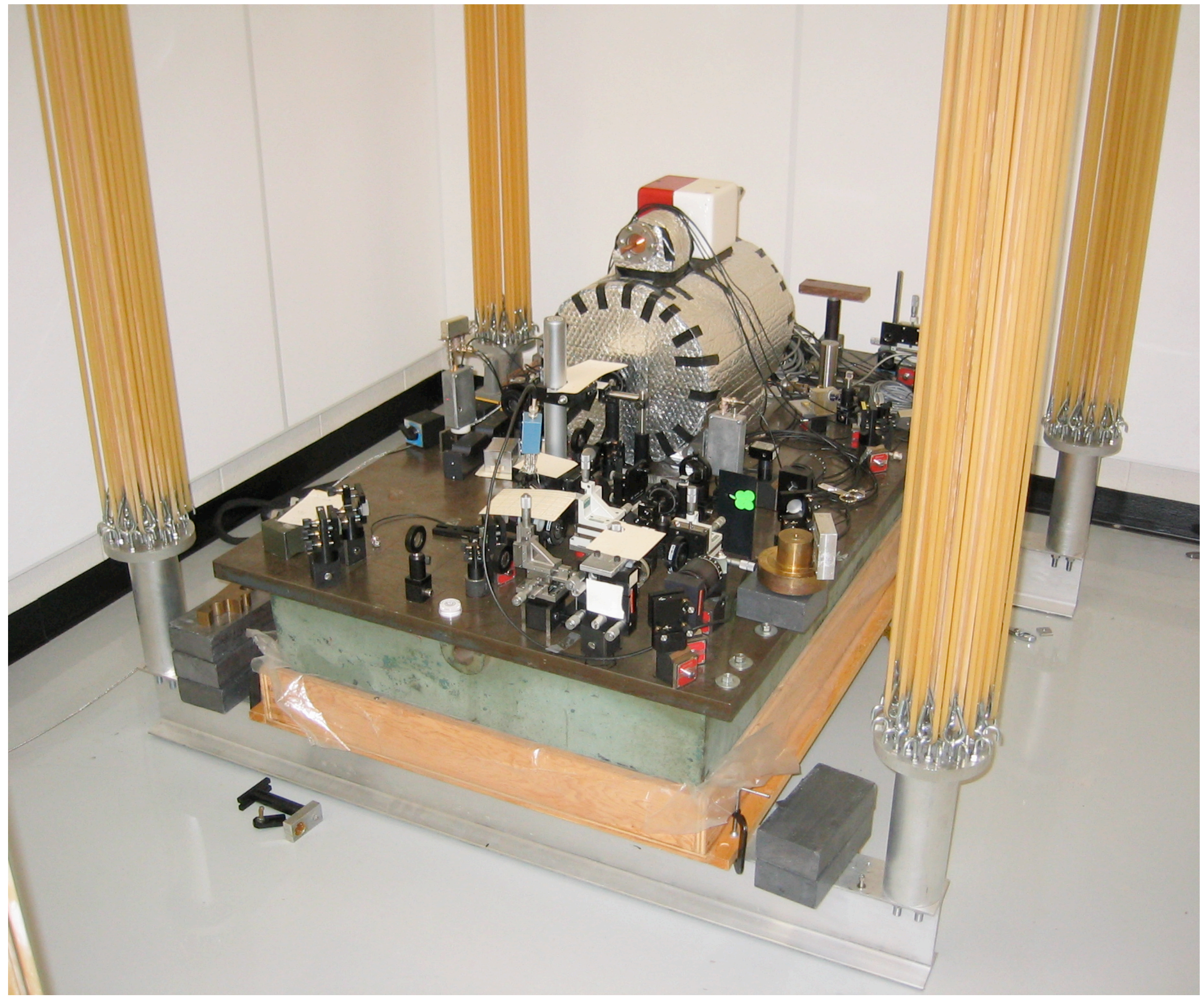
Isolated Cavities

- Resonances near 0.3 Hz
- Servo table height by heating rubber tubing
- Two independent cavity systems



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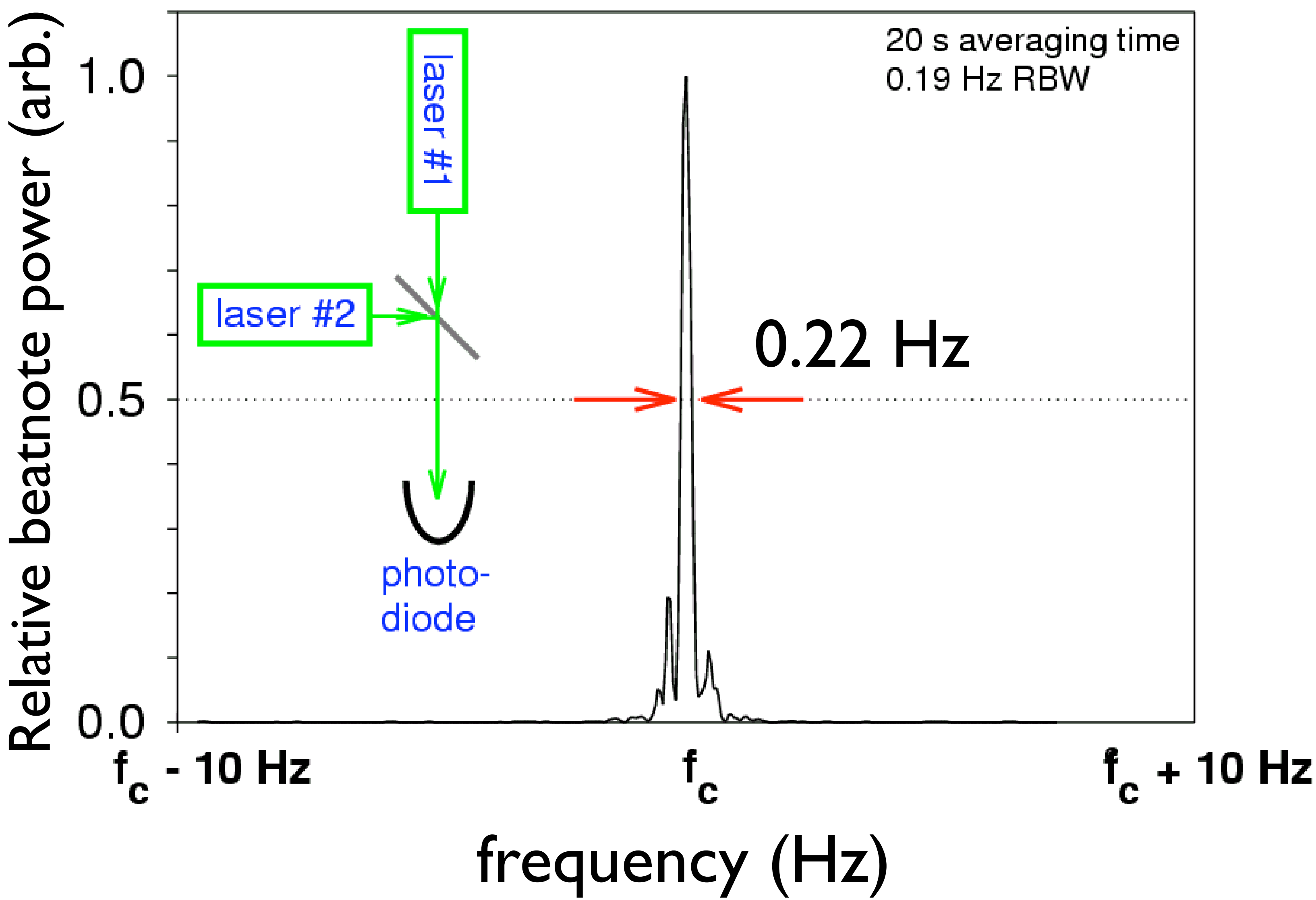
Beatnote between laser sources stabilized to independent cavities



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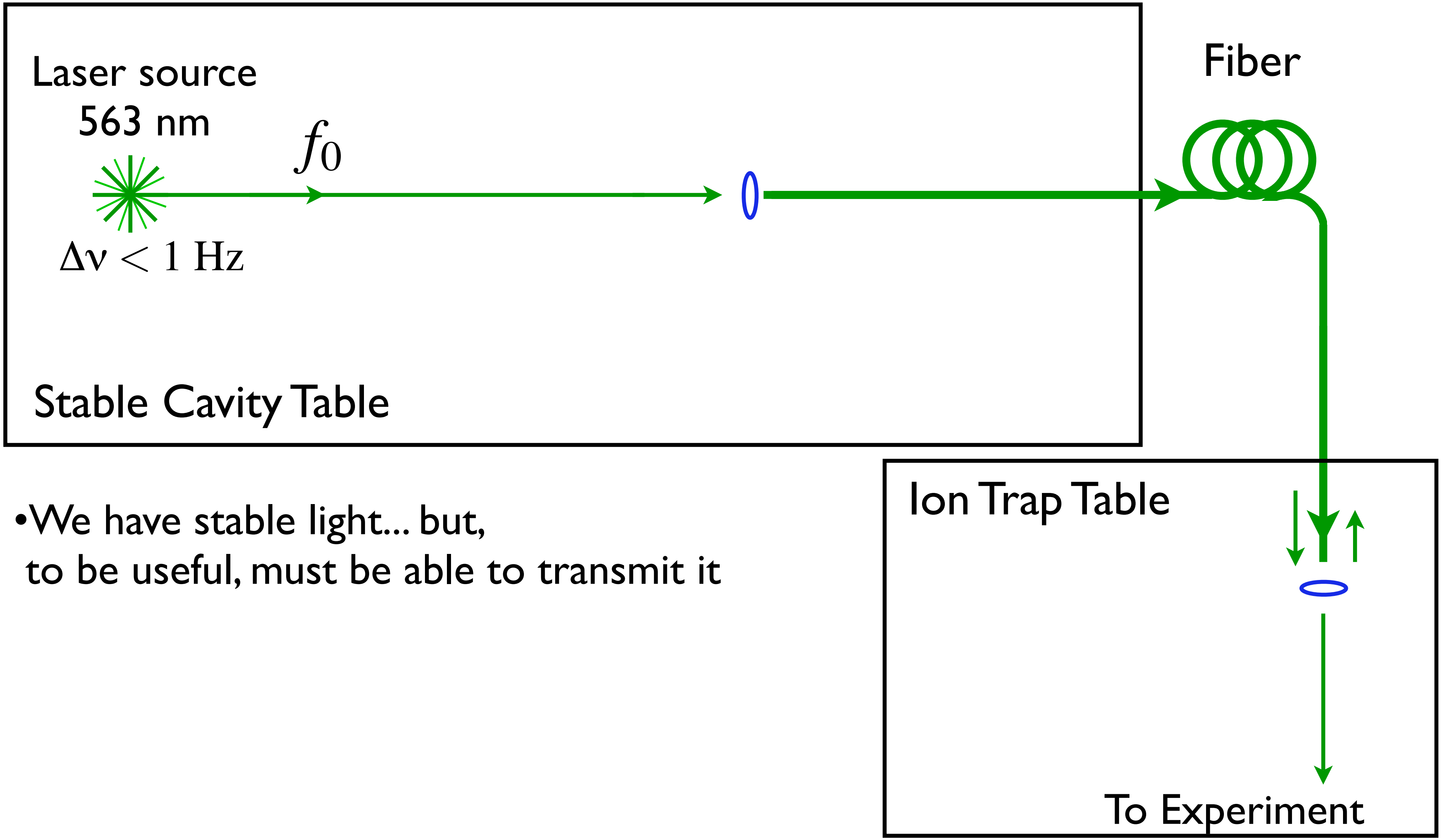
Cancellation of Fiber Noise



- We have stable light... but, to be useful, must be able to transmit it

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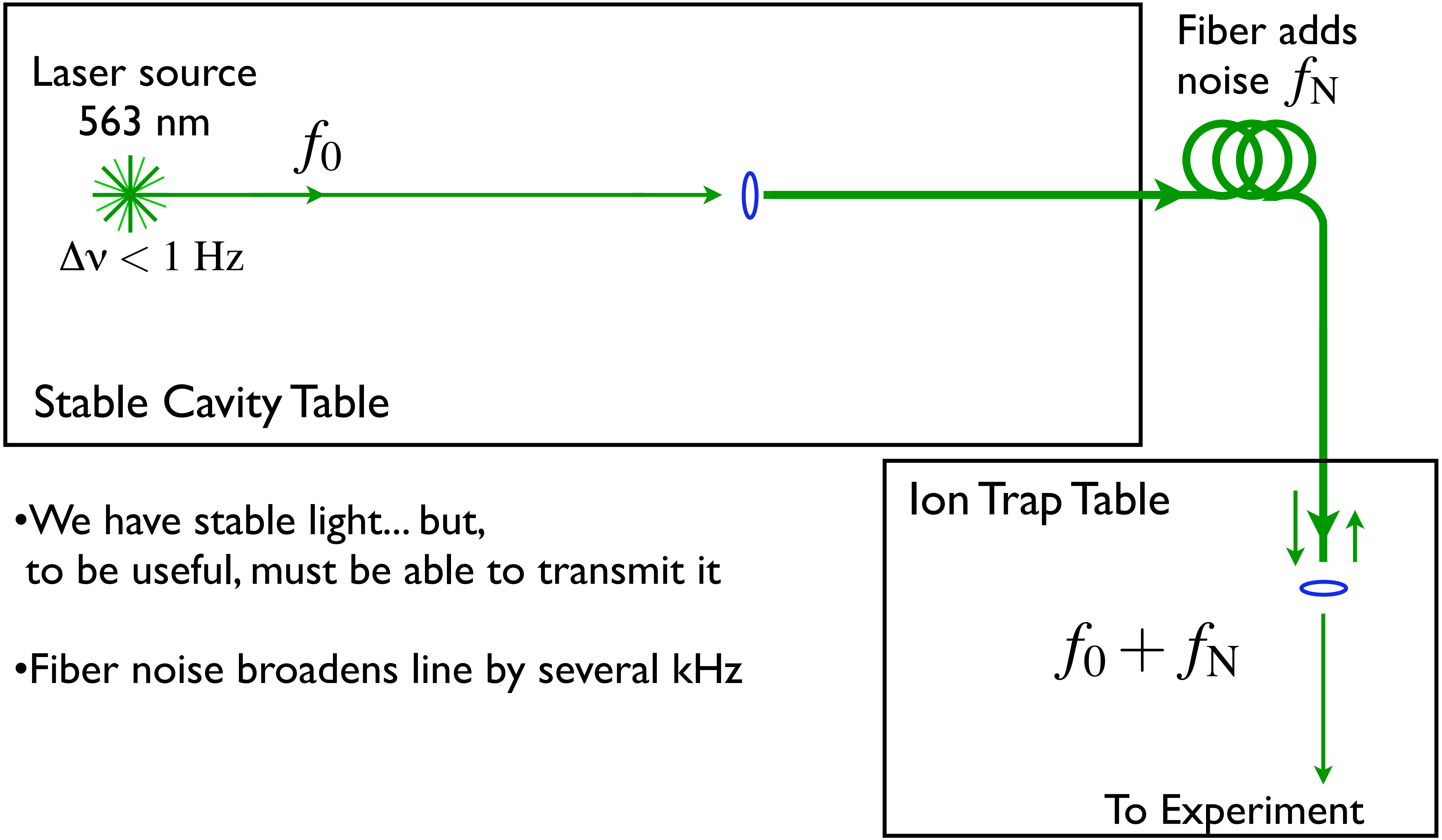
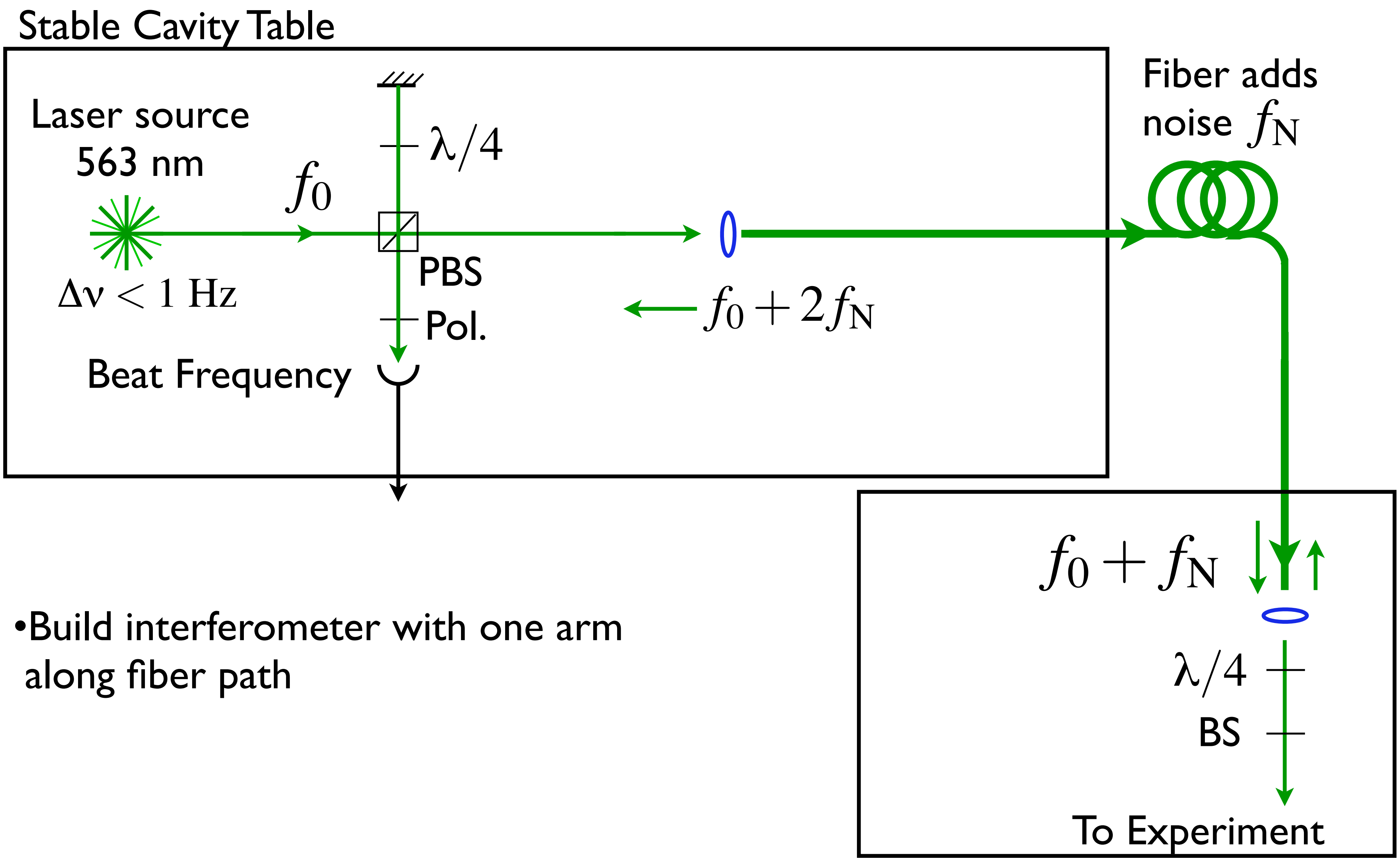


- We have stable light... but, to be useful, must be able to transmit it

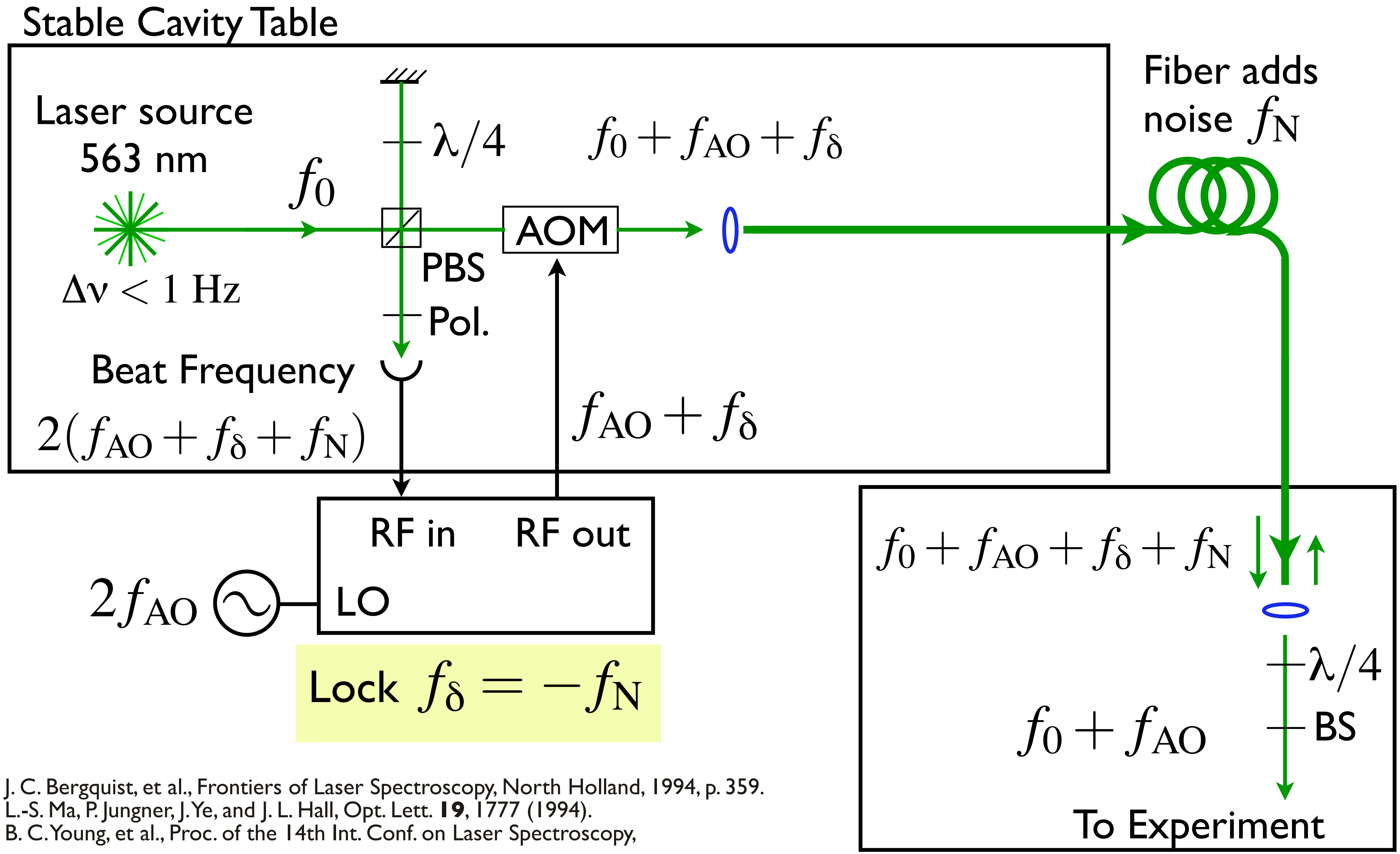
- Fiber noise broadens line by several kHz

Cancellation of Fiber Noise



- Build interferometer with one arm along fiber path

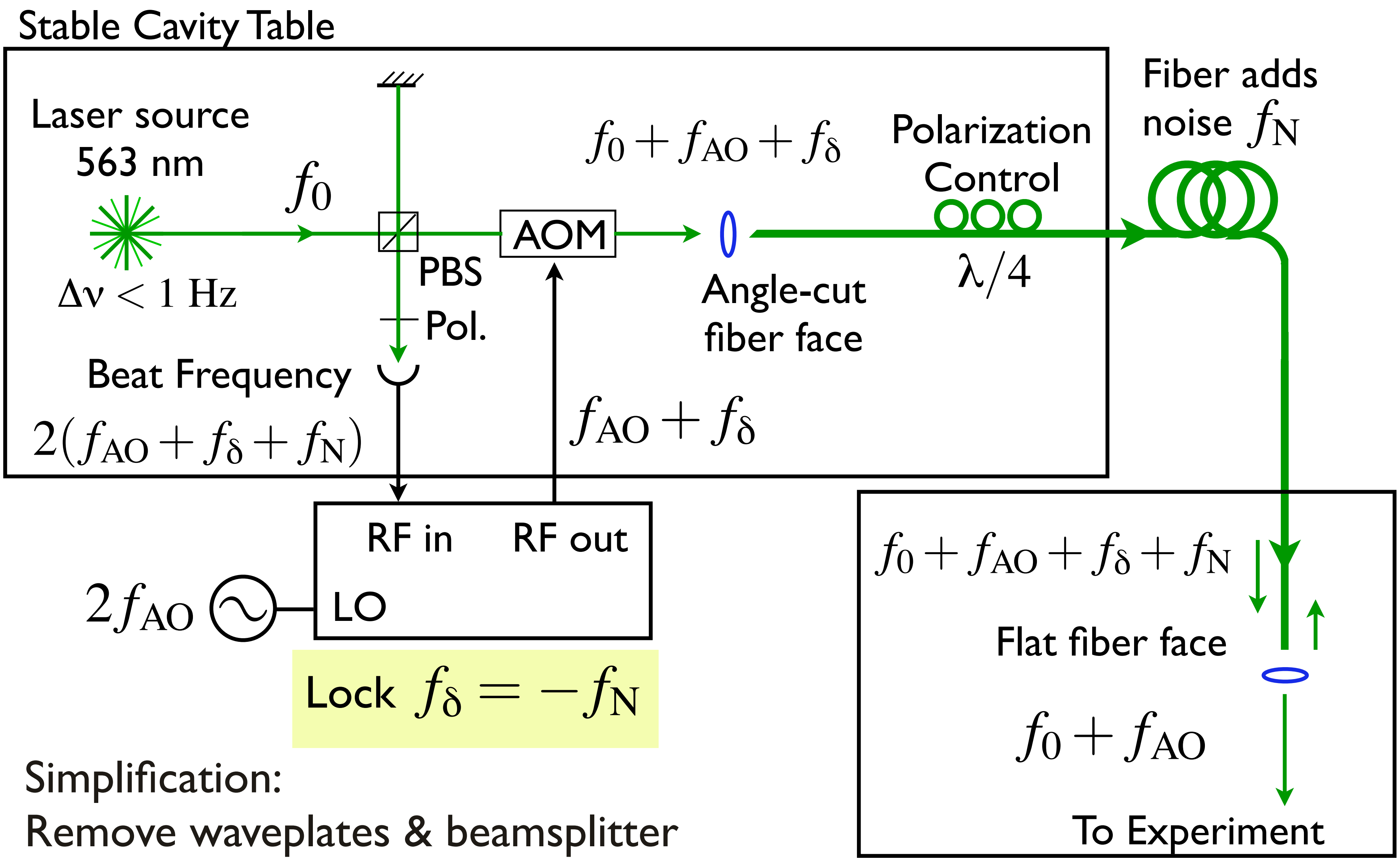
Cancellation of Fiber Noise



J. C. Bergquist, et al., Frontiers of Laser Spectroscopy, North Holland, 1994, p. 359.
L.-S. Ma, P. Jungner, J. Ye, and J. L. Hall, Opt. Lett. **19**, 1777 (1994).
B. C. Young, et al., Proc. of the 14th Int. Conf. on Laser Spectroscopy,

World Scientific, 1999, p.61.

Cancellation of Fiber Noise



Lock $f_\delta = -f_N$

Simplification:
Remove waveplates & beamsplitter

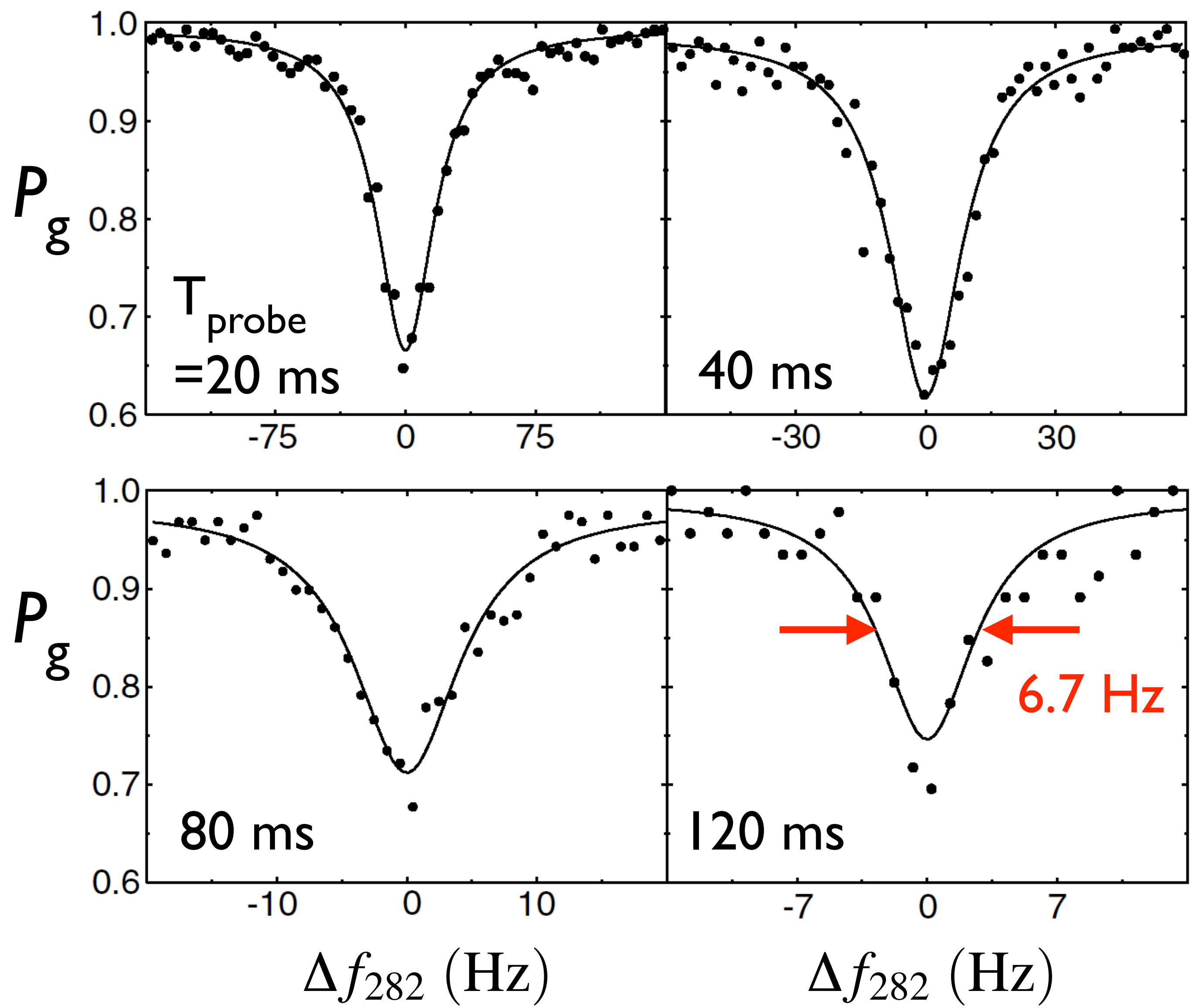
Absorption lineshapes

- Quantum-jump spectroscopy

-Rabi Excitation

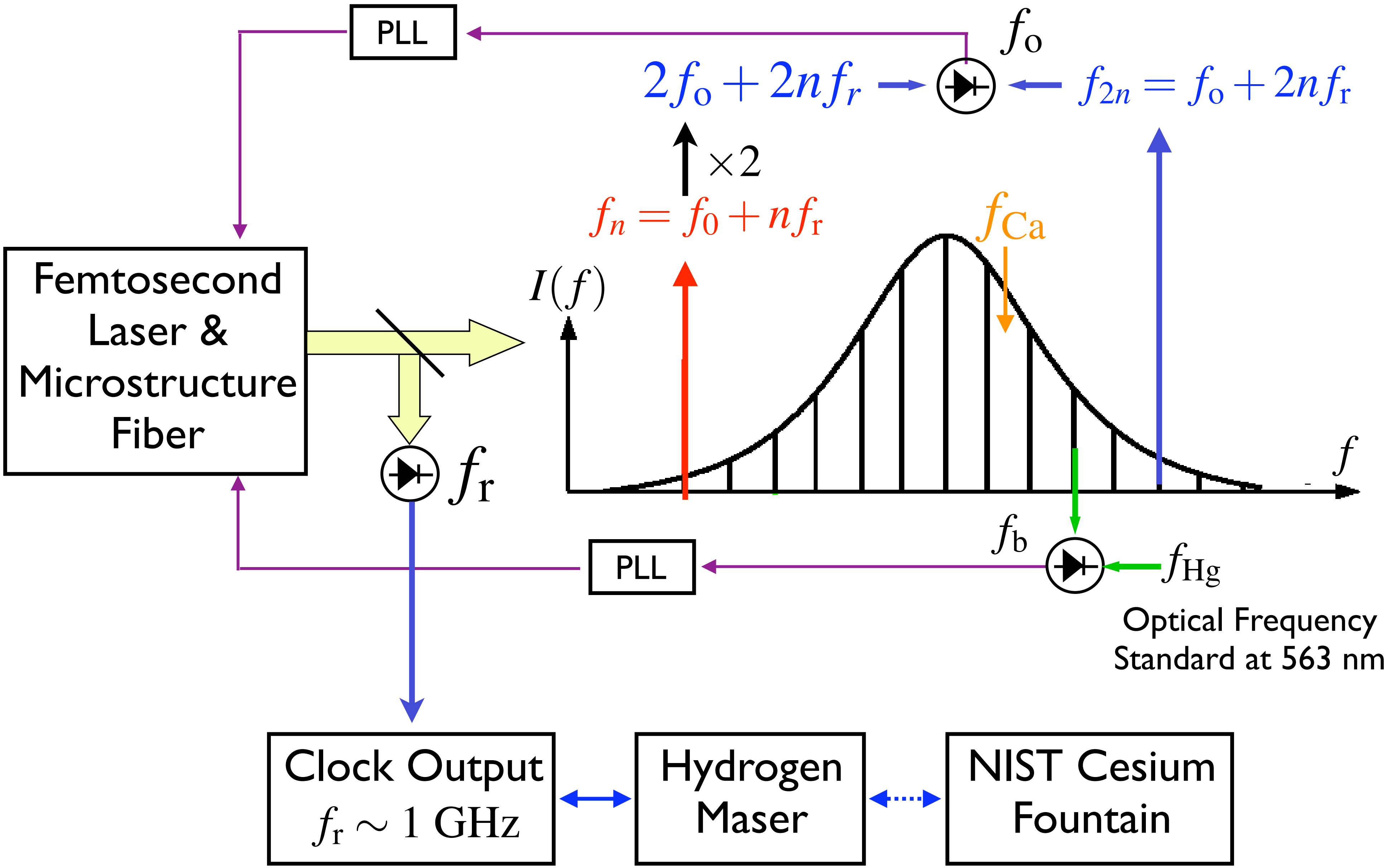
-Transform-limited linewidth

- Lock to transition by stepping across transition.



R. J. Rafac *et al.* PRL **85**, 2462 (2000)

Femtosecond comb system



S.A. Diddams, *et al.* Science **293**, 825 (2001)

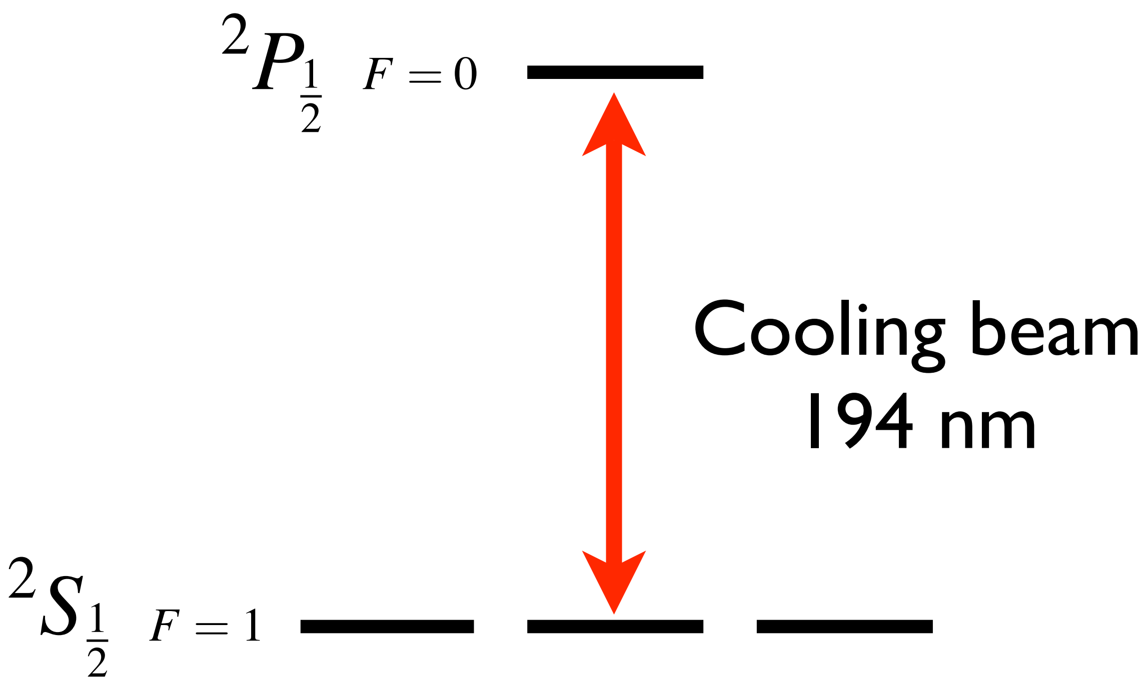
Systematic Frequency Shifts

Effect	Correction (Hz at 1.06 PHz)	Uncertainty (Hz)
2nd order Zeeman (B-field uncertainty)	1700, (typ., daily)	2.8
2nd order Zeeman (coefficient uncertainty)	0	2.6
${}^2D_{\frac{5}{2}}$ quadrupole shift	*Not evaluated*	10
H-maser frequency		4

Total fractional uncertainty: 10^{-14}

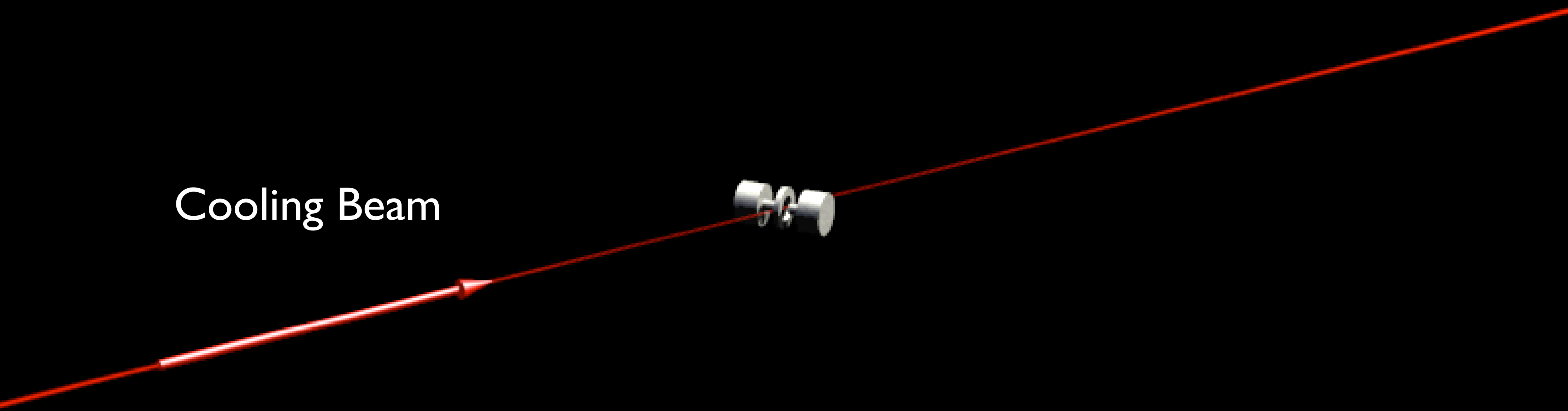
- Negligible (at this level): ac stark shifts (laser, trap),
  2nd order Doppler (micromotion, thermal),
  background collision shifts (helium),
  blackbody shift, fs comb noise.
- All effects *except quadrupole* should reduce below 10^{-18}

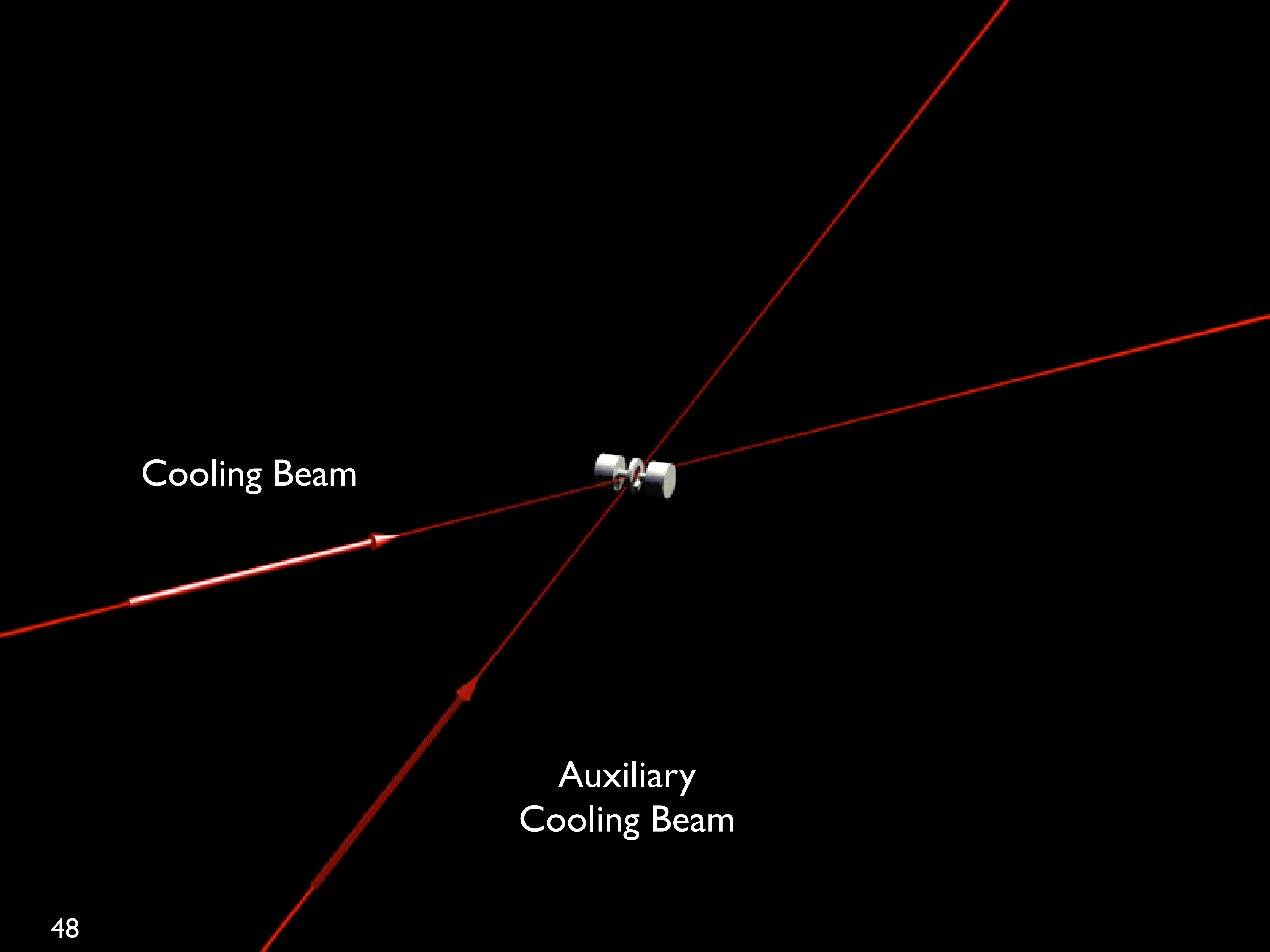
Avoiding dark states

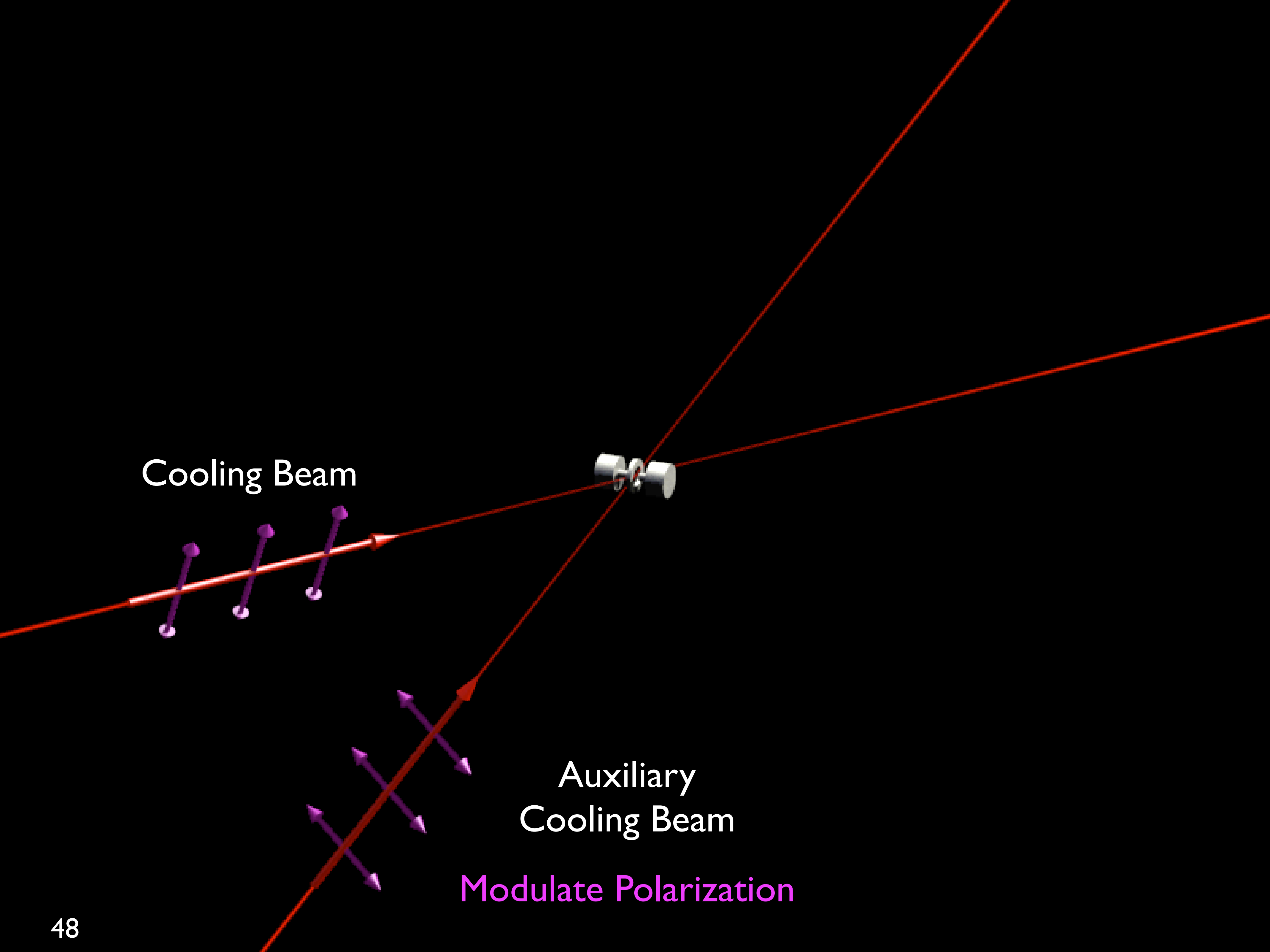


- Dark states for any polarization
- Limit fluorescence rate
- Destabilize with B-field or polarization modulation

D. J. Berkeland and M. G. Boshier, PRA, **65**, 033413 (2002)


Cooling Beam


Cooling Beam
Auxiliary
Cooling Beam


Cooling Beam
Auxiliary
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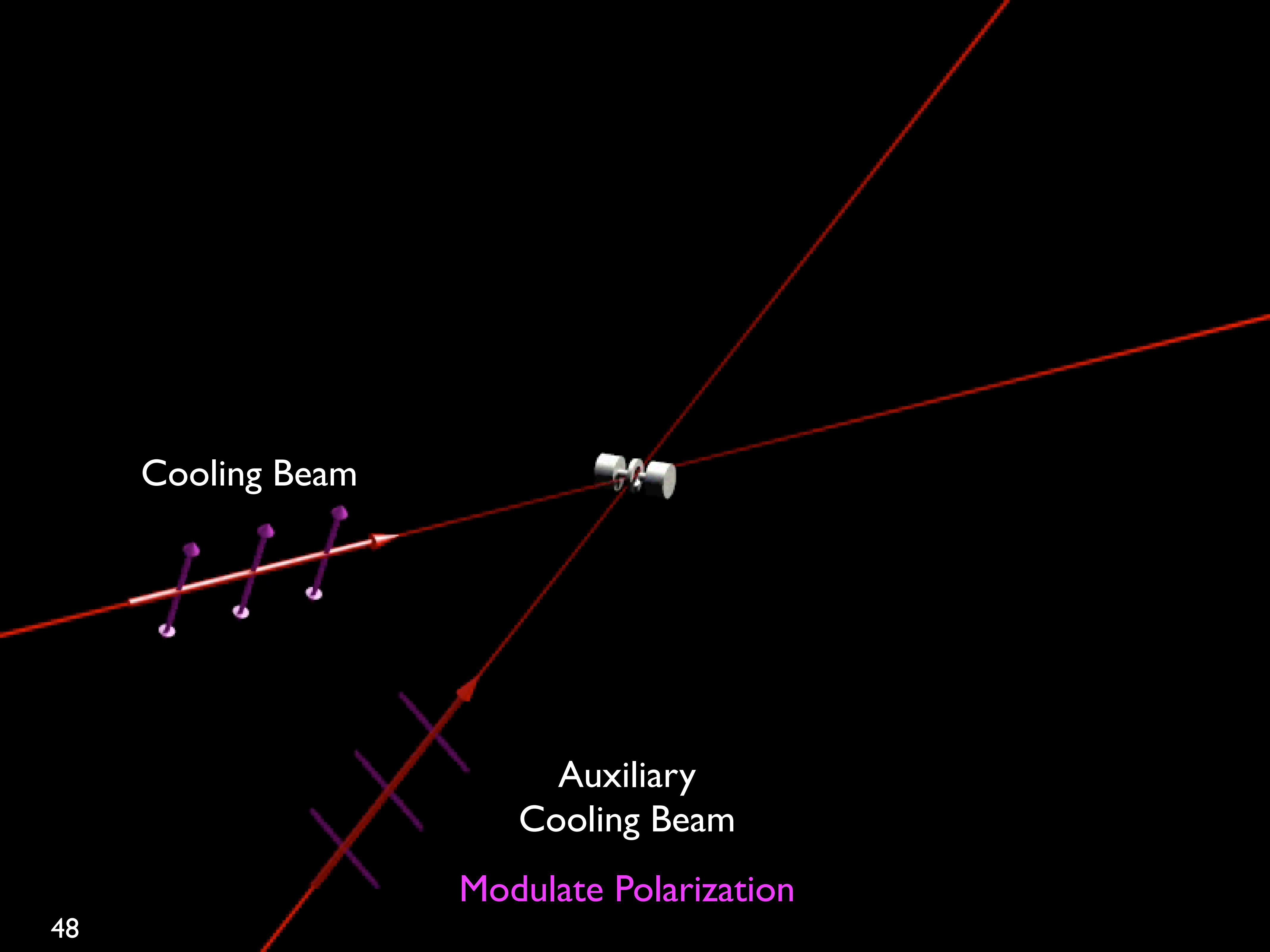
Modulate Polarization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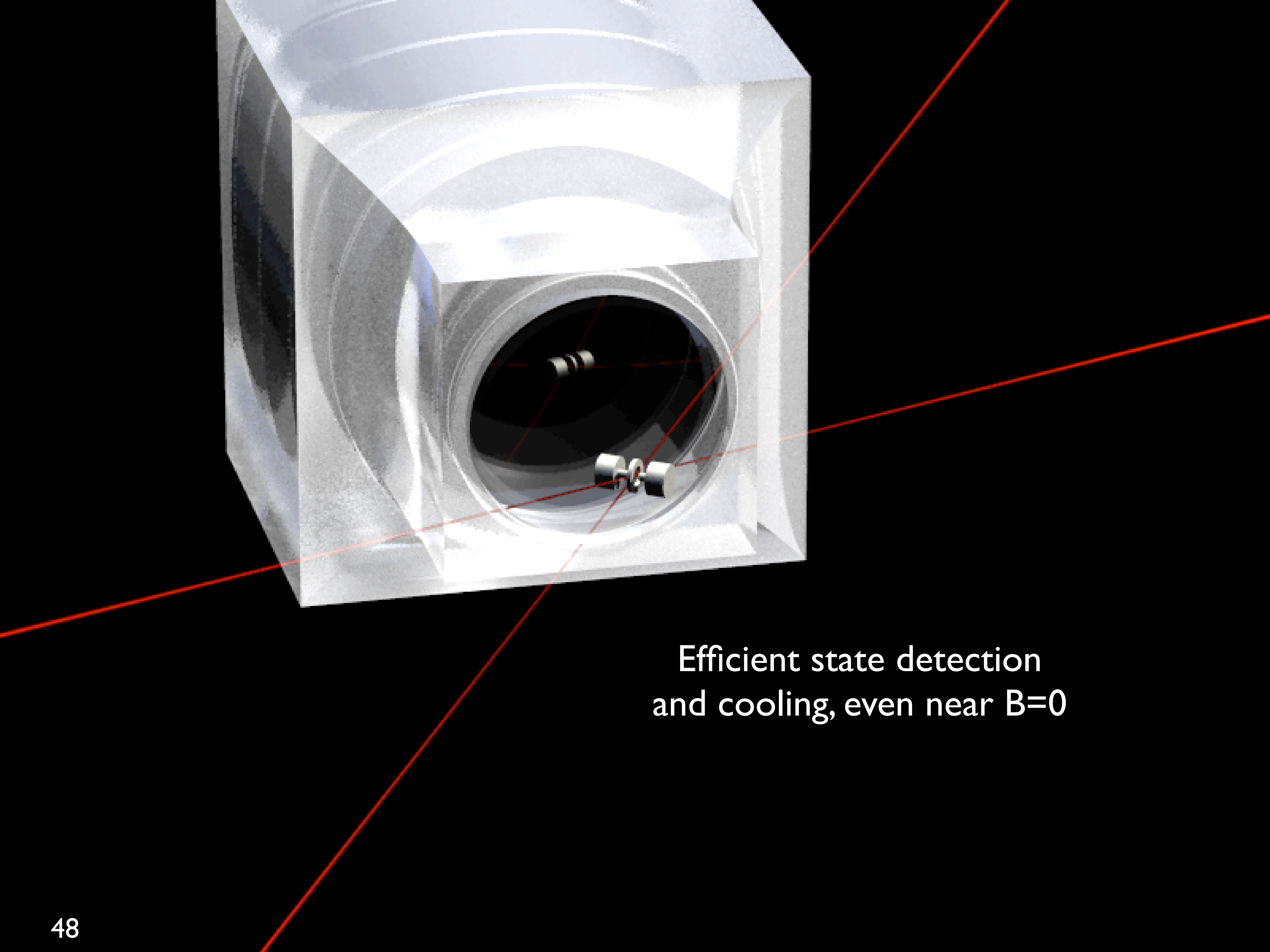


Efficient state detection
and cooling, even near B=0

Systematic Frequency Shifts

Effect	Correction (Hz at 1.06 PHz)	Uncertainty (Hz)
2^{nd} order Zeeman (B-field uncertainty)	10, (typ., daily)	<0.1
2^{nd} order Zeeman (coefficient uncertainty)	0	0.01
${}^2D_{\frac{5}{2}}$ quadrupole shift	*In progress*	???
H-maser frequency		1

Total fractional uncertainty: 10^{-14}

- Negligible (at this level): ac stark shifts (laser, trap), 2^{nd} order Doppler (micromotion, thermal), background collision shifts (helium), blackbody shift, fs comb noise.
- All effects *except quadrupole* should reduce below 10^{-18}

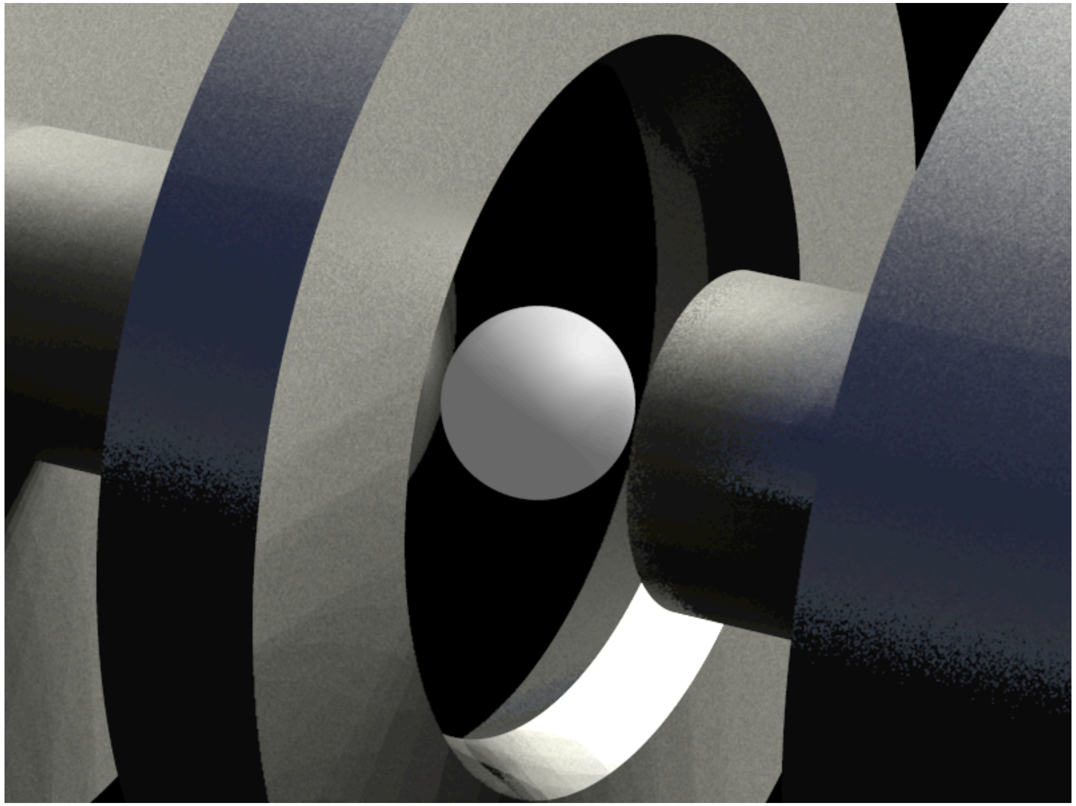
The Quadrupole Shift

•Shift due to coupling of $^2D_{5/2}$-state electric quadrupole moment with stray E-field gradients

For *ideal* spherical rf trap:

•No static electric fields

•Transition frequency independent of quantization axis orientation



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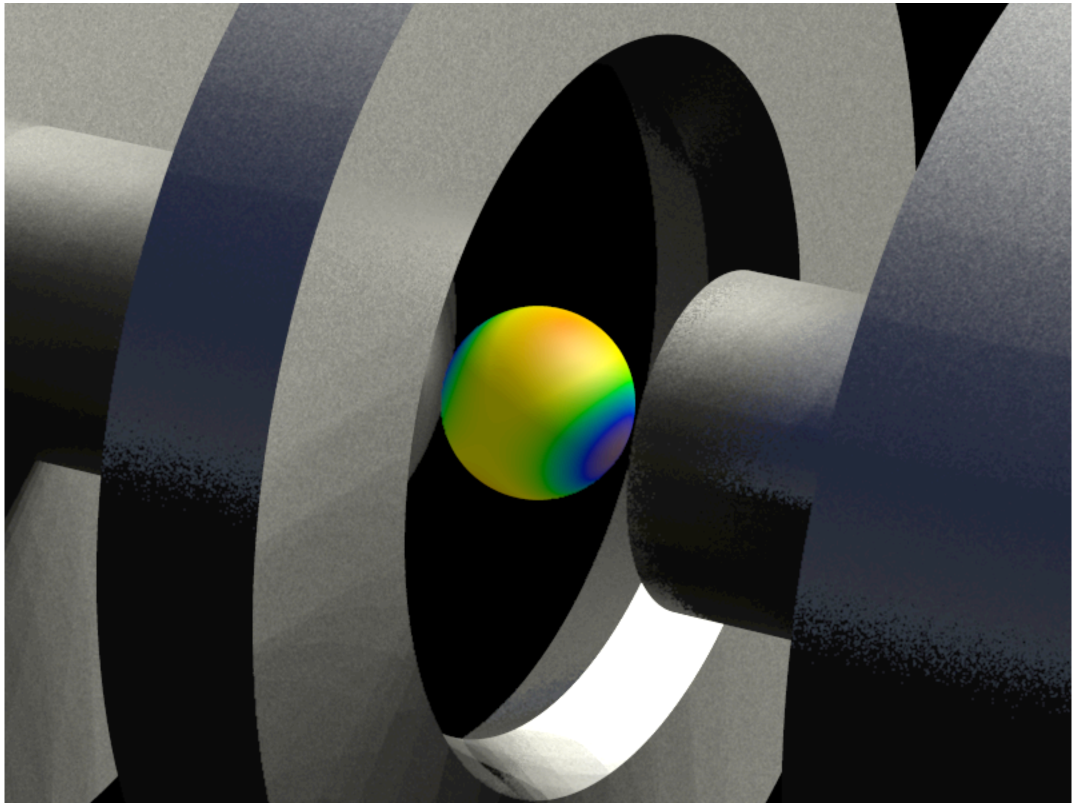
The Quadrupole Shift

- Shift due to coupling of $^2D_{5/2}$-state electric quadrupole moment with stray E-field gradients

For *real* spherical rf trap:

- Electric patch potentials
- Transition frequency is a function of quantization axis orientation



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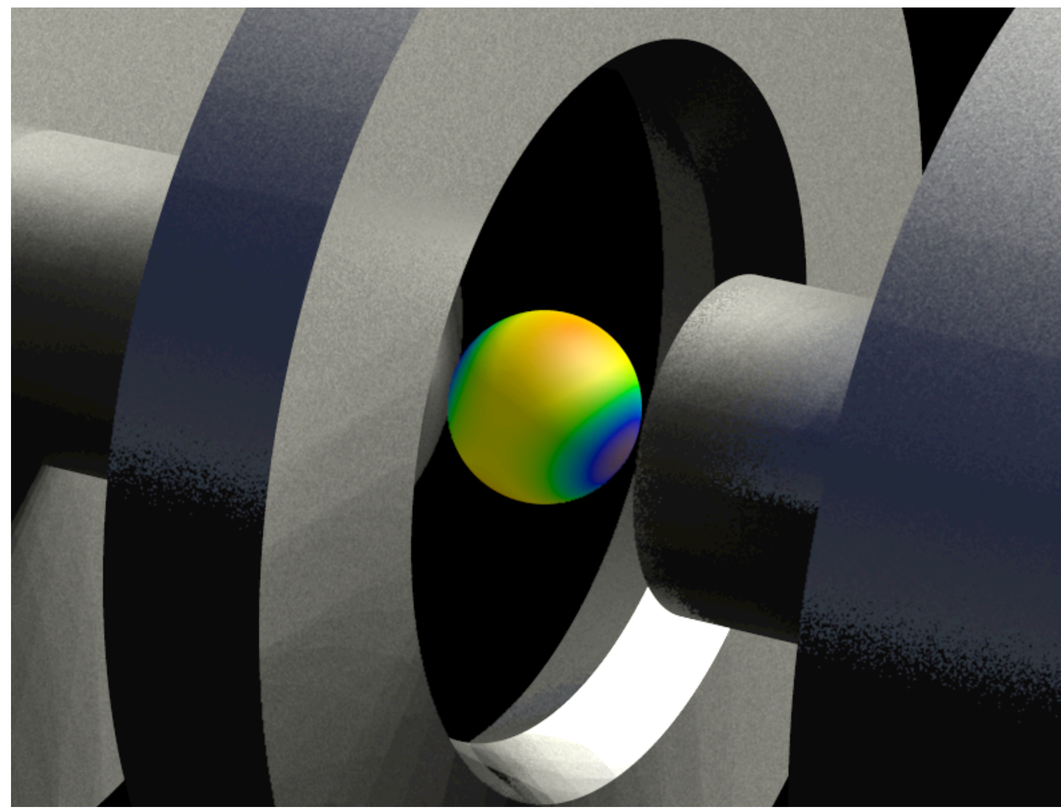
Evaluating Quadrupole Shift

•Quadrupole shift averages to zero over three orthogonal quantization axes [W. M. Itano, J. Res. NIST **105**, 829 (2000)]

•Magnitude expected to be under 10^{-15} (1 Hz)

$$10^3\ \mathrm{V/cm^2} \Longrightarrow \approx 1\ \mathrm{Hz}$$

•Need stable flywheel for this measurement!



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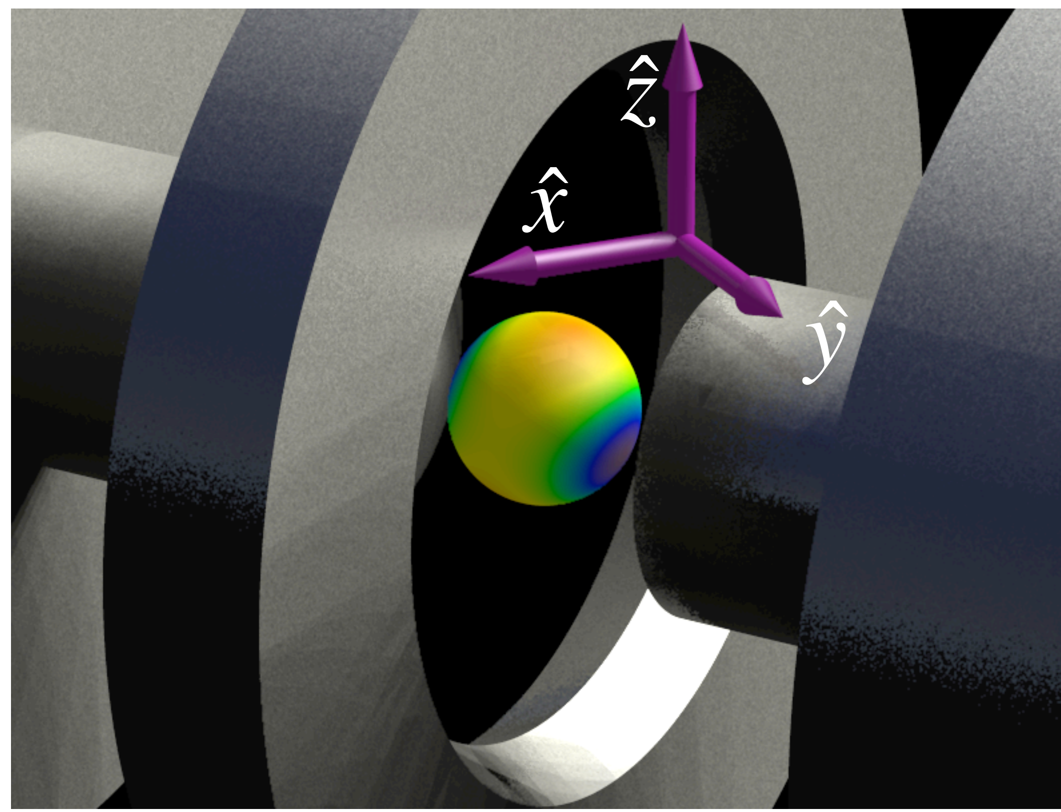

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Evaluating Quadrupole Shift

- Quadrupole shift averages to zero over three orthogonal quantization axes [W. M. Itano, J. Res. NIST **105**, 829 (2000)]

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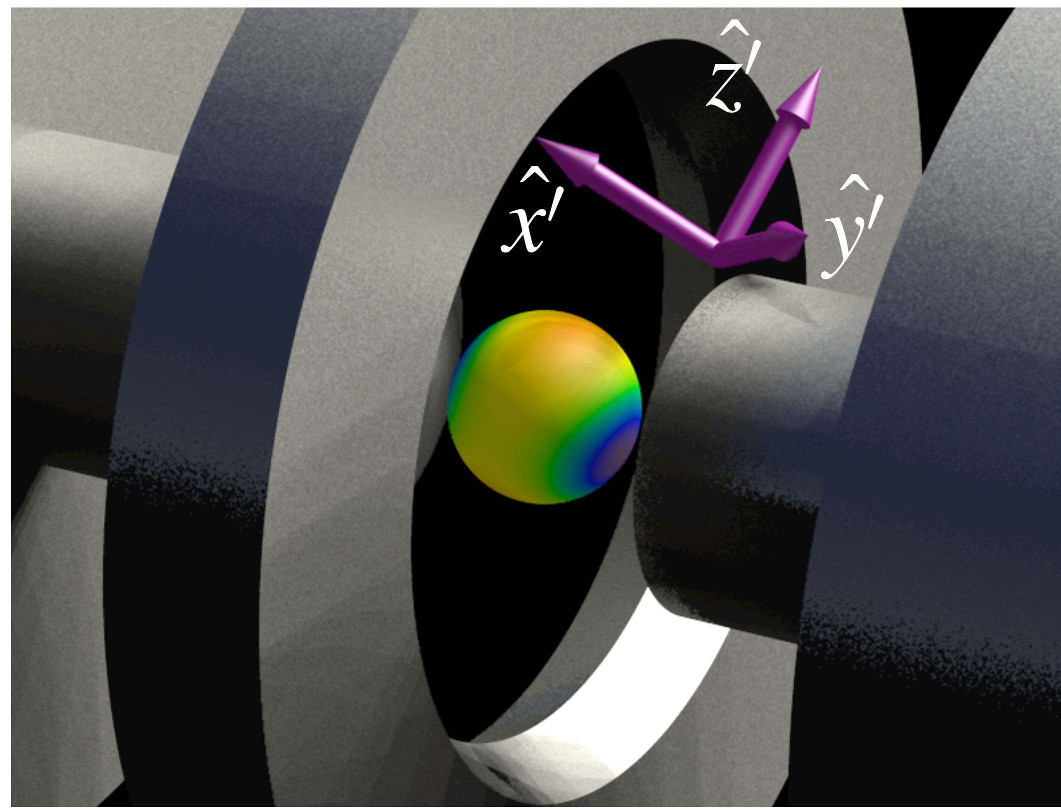
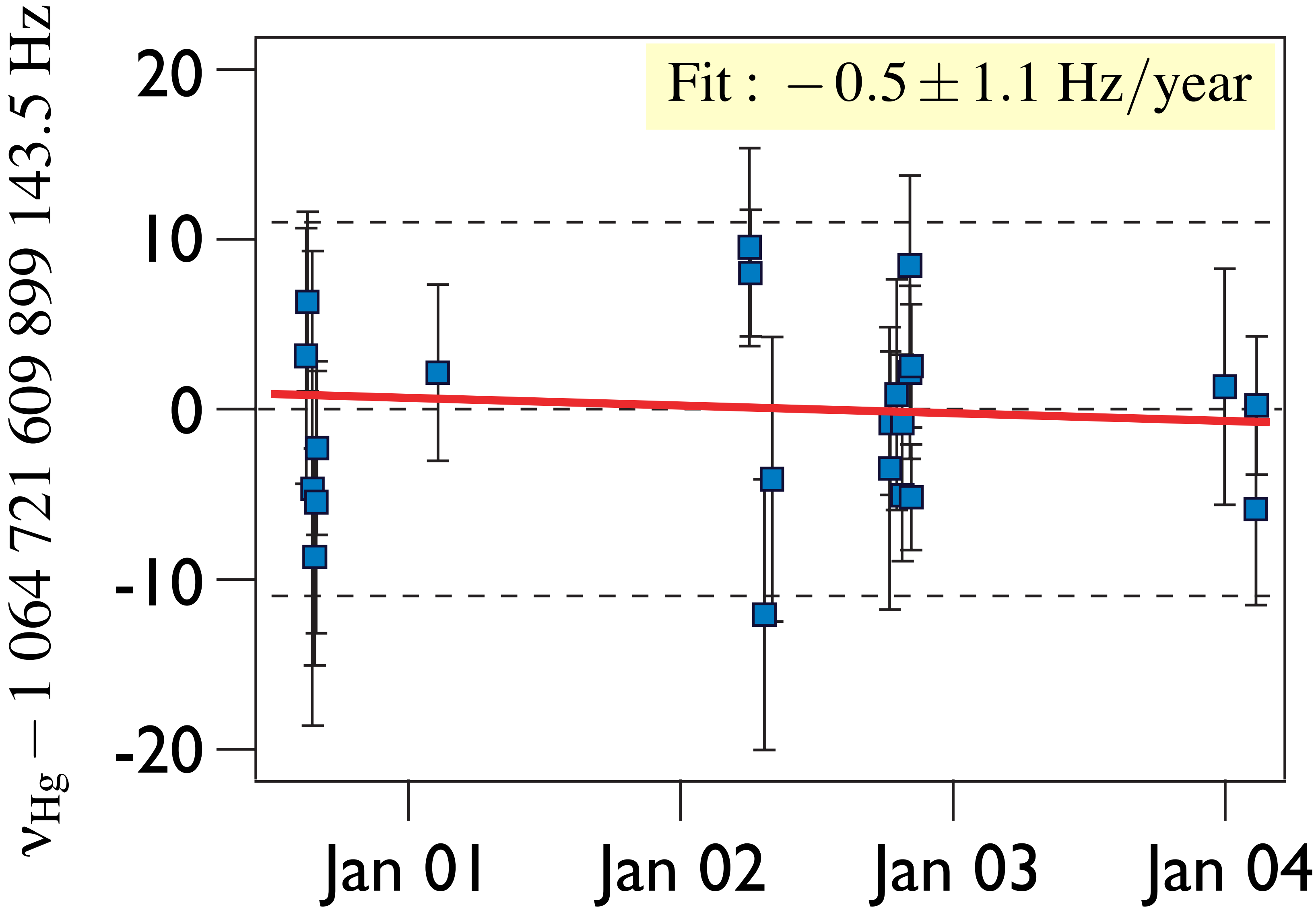


Absolute frequency measurements



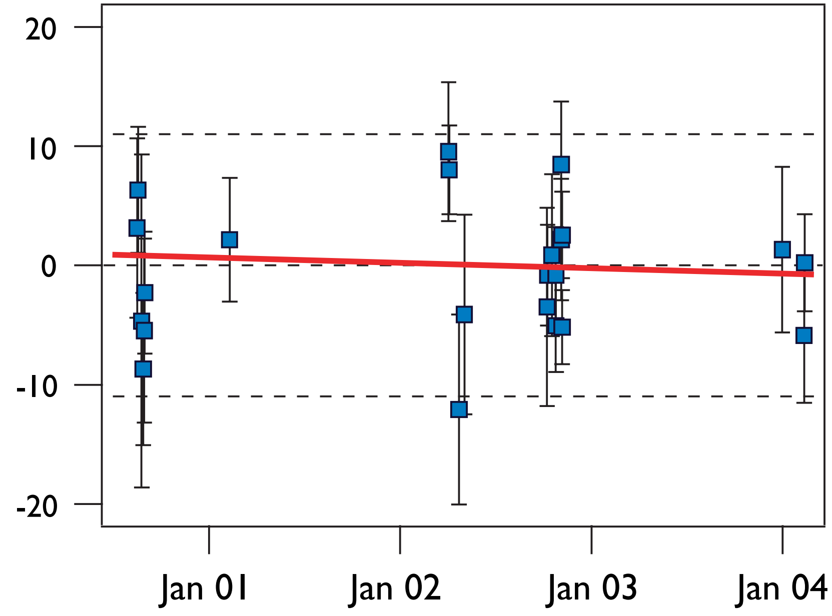
(Statistical error bars only)

S. Bize *et al.*, PRL **90**, 150802 (2003).

Absolute frequency measurements

- No significant long-term change observed over three years.
  - -Fluctuations comparable to that of Cs fountain
  - -Promising for testing of stability of fundamental constants

- No significant change with different traps or trap surfaces (Au, Mo)
  - -Suggests low quadrupole shift



Transition Frequencies

- Clock comparisons may provide the best test of present-day changes in physical constants.

For example, look at Hg vs Cs, express transition frequencies as:

$$\nu_{\mathrm{Hg}} \approx R_{\infty} c F_{\mathrm{Hg}}(\alpha),$$
$$\nu_{\mathrm{Cs}} \approx g_{\mathrm{Cs}}(m_e/m_p)\alpha^2 R_{\infty} c F_{\mathrm{Cs}}(\alpha)$$

$$\alpha\frac{\partial}{\partial\alpha}(\ln F_{\mathrm{Hg}}(\alpha)) \approx -3.2$$

$$\alpha\frac{\partial}{\partial\alpha}(\ln F_{\mathrm{Cs}}(\alpha)) \approx +0.8$$

$$\Longrightarrow \quad \frac{\nu_{\mathrm{Cs}}}{\nu_{\mathrm{Hg}}} \approx g_{\mathrm{Cs}}(m_e/m_p)\alpha^{6.0}$$

Test stability of this ratio

V. A. Dzuba, V. V. Flambaum, and J. K. Webb, PRA **59**, 230 (1999).

S. Bize *et al.*, PRL **90**, 150802 (2003).

Results

- With 10^{-14} accuracy and 3 years measurement, fractional change in $\nu_{\mathrm{Cs}}/\nu_{\mathrm{Hg}}$ is $\leq \pm 6 \times 10^{-15}\mathrm{yr}^{-1}$

- *If* all variation in $\nu_{\mathrm{Cs}}/\nu_{\mathrm{Hg}}$ is due to α,
  constrain present-day variation of α :

$$|\dot{\alpha}/\alpha| \leq 1 \times 10^{-15}\mathrm{yr}^{-1}$$

- Look at measurements with other species
  to tighten constraints.

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Other recent Results

- $\nu_{\mathrm{Rb}}/\nu_{\mathrm{Cs}}$ (microwave) Measurement interval: 4 years

$$\frac{\Delta(\nu_{\mathrm{Rb}}/\nu_{\mathrm{Cs}})}{(\nu_{\mathrm{Rb}}/\nu_{\mathrm{Cs}})} = (0.2 \pm 7.0) \times 10^{-16}\ \mathrm{yr}^{-1}$$

H. Marion *et al.*, PRL **90**, 150801 (2003).

- $\nu_{\mathrm{H}}/\nu_{\mathrm{Cs}}$ (Optical) Measurement interval: 4 years

$$\frac{\Delta(\nu_{\mathrm{H}}/\nu_{\mathrm{Cs}})}{(\nu_{\mathrm{H}}/\nu_{\mathrm{Cs}})} = (3.2 \pm 6.4) \times 10^{-15}\ \mathrm{yr}^{-1}$$

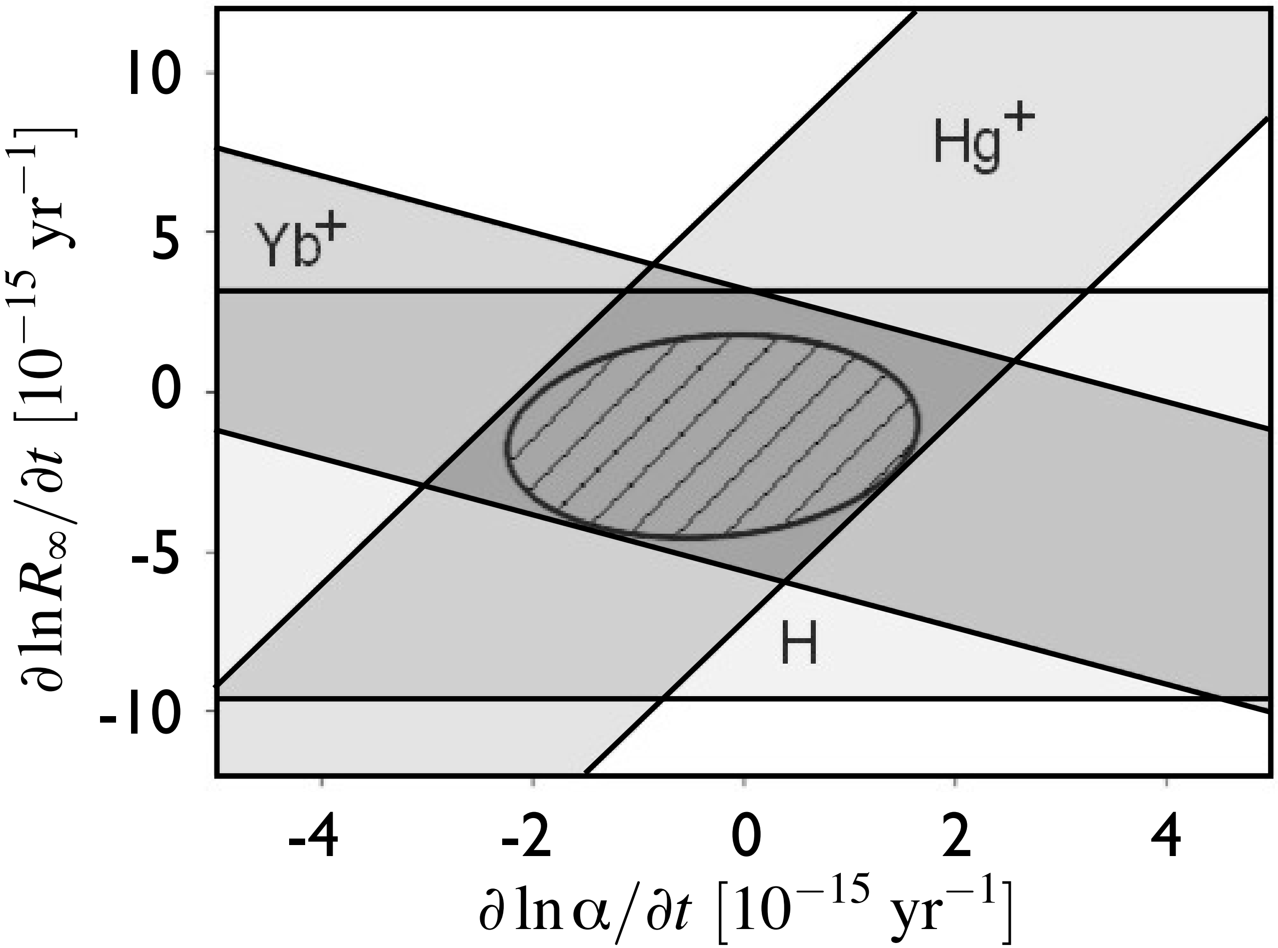
M. Fischer et al., arXiv:physics/0312086

- $\nu_{\mathrm{Yb}^+}/\nu_{\mathrm{Cs}}$ (Optical) Measurement interval: 3 years

$$\frac{\Delta(\nu_{\mathrm{Yb}^+}/\nu_{\mathrm{Cs}})}{(\nu_{\mathrm{Yb}^+}/\nu_{\mathrm{Cs}})} = (-1.2 \pm 4.4) \times 10^{-15}\ \mathrm{yr}^{-1}$$

E. Peik et al., arXiv:physics/0402132

Limits with other standards



H
M. Fischer et al.,
arXiv:physics/0312086

Yb+
E. Peik et al.,
arXiv:physics/0402132

$$\frac{\partial \ln \alpha}{\partial t} = (-0.3 \pm 2.0) \times 10^{-15}\ \mathrm{yr}^{-1} \qquad \frac{\partial \ln R_\infty}{\partial t} = (-1.5 \pm 3.2) \times 10^{-15}\ \mathrm{yr}^{-1}$$

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Present work and Outlook

- Improvements to accuracy:
  - Reduced operating B-field, added shielding, B-field coils installed near ion trap
  - Proceed with evaluation of quadrupole shift;

- Improvements to stability:
  - Quench D-state (reduce dead time)

- Comparison of two Hg+ clocks

- Other optical-optical clock comparisons (Ca,Sr,Yb,Al+)

Acknowledgments

Femtosecond Comb Group

- A. Bartels
- S. A. Diddams
- L. Hollberg

Ion Trap Group

- J. C. Bergquist
- R. E. Drullinger
- W. M. Itano
- W. H. Oskay
- C. E. Tanner*
- D. J. Wineland

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- T. P. Heavner
- S. R. Jefferts
- T. E. Parker

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